THE MILKY WAY

The Milky Way in Sagittarius.

Composite of two photographs taken by Baade with the 18-inch Schmidt camera at Mount Palomar.

THE HARVARD BOOKS ON ASTRONOMY

Edited by

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THE MILKY WAY

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1

PRESENTING THE MILKY WAY

WHEN JUPITER SUMMONED THE GODS TO COUNCIL TO END the frightful condition of things on earth "they obeyed the call, and took the road to the palace of heaven. The road, which anyone may see in a clear night, stretches across the face of the sky, and is called the Milky Way. Along the road stand the palaces of the illustrious gods; the common people of the skies live apart on either side." *

In this book we invite you to join us on a brief tour along the road to the heaven of the Greeks. Modern science has provided the transportation facilities, and, without it being necessary for you to leave your comfortable chair, we should like to show you the sights. Our plan is briefly as follows. We shall start off with a quiet evening at home where we shall get out maps and photographs of the territory that we are about to explore. We shall introduce you to some of the intricacies of our celestial vehicles and we shall then get under way. First we shall pay some casual visits to the sun's nearest neighbors, but soon we move on to sound the real depths of our universe. We shall visit big

* Bulfinch's "Mythology."

stars and little stars, systems of stars within the larger system. This larger system, seen by us as the Milky Way, is a very flat stellar aggregation in which the stars move in intricate, though basically simple, paths. On the way we shall frequently have to pause to clear the ever-present cosmic dust from our traveling clothes. We shall, of course, wish to linger awhile on our visits to the palaces of the illustrious gods that are along the main road, and also, every now and again, we shall invite you to join us on a side excursion through the places of the common people far from the main road.

In spite of our desire to show you all the sights, we shall have to limit our celestial itinerary. Not infrequently we shall see along the road posters saying: "Unexplored territory; heavy fog," or more encouraging signs: "Men at work; pass at your own risk." For the Milky Way is by no means sufficiently well explored to render all of it safe for celestial tourists. We hope that, when you return, you will not regret having taken the time for such a long trip, and that you will still be curious about what lies beyond the fog. Some of our guests may perhaps be irritated by those forbidding posters along the road and will desire to start explorations of their own.

So, let us get our maps and photographs and start on the journey through the Milky Way.

The Milky Way

In most of the United States and Europe the best general view of the Milky Way can be had in mid-summer on a moonless night shortly after sunset. The northern cross of the constellation of Cygnus is then directly overhead, Arcturus is on its way down to the west and in the northeast the W-shaped constellation of Cassiopeia is rising into view. If you are far from the glare of city lights and neon

signs, you will have no difficulty in locating the faintly shimmering band of the Milky Way that can be traced through Cassiopeia and Cepheus to Cygnus and then down toward the horizon through the constellations of Aquila and Sagittarius.

The Milky Way from Cassiopeia to Cygnus has the appearance of a single silvery band of varying width, but between Cygnus and Sagittarius we can discern two distinct bands separated by a dark space called the Great Rift. The eastern branch is by far the more conspicuous one of the two. The western branch is quite bright in Cygnus, still discernable in Aquila, but it is lost in the dark wastes of Ophiuchus.

There are some very conspicuous bright spots along the summer Milky Way. The star clouds in Cygnus are right overhead. While they do put on a fine show they lose out in comparison both with the cloud in Scutum—to which E. E. Barnard referred as the "gem of the Milky Way"—and with several bright clouds in Sagittarius. The Milky Way is still bright in the constellation of Cepheus, but even a cursory inspection will show that the Milky Way north of Cygnus does not shine nearly so brightly as does the branch to the east of the Great Rift.

What lies beyond the horizon? Our summer night progresses, and Sagittarius, Aquila, and Cygnus gradually set. But as Cassiopeia rises toward the meridian other parts of the Milky Way come into view and we can follow it through Perseus, Auriga and Taurus. The part of the Milky Way south of Taurus and Auriga is lost in the summer dawn, but if we wait until early fall we can follow the Milky Way southward through Gemini, Orion, Monoceros, and Canis Major. The Milky Way from Cygnus through Cassiopeia to Canis Major is, however, much less conspicuous than the branches on either side of the Great

Rift. In Auriga and Taurus the Milky Way narrows down to a trickling little stream that is quite insignificant in comparison to the brighter sections of the summer Milky Way.

What happens to the Milky Way south of Sagittarius and south of Canis Major? Those parts of the Milky Way are invisible from the latitudes of New York or Paris and we shall have to travel southward if we wish to see them. The whole Milky Way passes in review for a year-around observer in the southern tip of Florida, but for a good view we had better go down to the equator.

The section of the Milky Way from Sagittarius through Scorpio, Norma, Circinus, Centaurus, Crux (the Southern Cross) and Carina has great brilliance. In general appearance it resembles to some extent our summer Milky Way between Cygnus and Sagittarius. The star cloud in Norma is not unlike the Scutum cloud and the Carina cloud appears rather similar to the Cygnus cloud. We miss in this section of the Milky Way the pronounced dark rift found north of Sagittarius, but then, the southern branch can boast of the black Coalsack, which is "blacker" than anything up north.

The remaining section of the southern Milky Way, which runs from Canis Major through Puppis and Vela to Carina, is in general not unlike the northern Milky Way in Cepheus and Cassiopeia. There are no marked irregularities, and the band remains clearly visible along its entire course.

Ours are the days of large and powerful telescopes and you might well ask if there is much point to a careful study of the naked-eye appearance of the Milky Way. We earnestly believe that there is much to be learned from a survey without the use of a telescope or photographic camera. Our eyes happen to be the finest pair of wide-angle binoculars that has yet been made. A telescope is useful

in the study of fine details for comparatively small sections of the sky, but no instrument is capable of revealing the grand sweep of the entire Milky Way as well as the human eye. On a good night we can intercompare directly portions of the Milky Way that are as far apart as Sagittarius and Cassiopeia. Such direct rapid intercomparisons reveal one of the most important properties of the Milky Way, namely, that the width and brightness of the band differs greatly from one section to another. The Milky Way attains its greatest width as well as its maximum brightness in Sagittarius. The half of the Milky Way from Cygnus through Sagittarius to Carina is generally very much brighter and wider than the half that runs from Cygnus through Orion to Carina.

Fig. 1.—Sir William Herschel.
National Portrait Gallery, London.

Telescopic Views

A good powerful pair of binoculars, or a small visual telescope, will reveal that the Milky Way is a composite effect produced by thousands upon thousands of faint stars. As we sweep across the sky with our telescope, the total number of stars in the field of view increases markedly as we approach the Milky Way. More than a century ago, Sir William Herschel spent several years sweeping the sky—or as he called it, "gauging the heavens"—with his giant reflectors. His son, John, later carried out the same plan for the southern sky. Their studies gave accurate data on the rate at which the star numbers increase toward the

Milky Way. They showed that the rate of increase is very much larger for the fainter stars than for the brighter ones. If we compare two fields—one in the Milky Way, and the other at right angles to the Milky Way at the so-called galactic poles—with a 3-inch telescope, we get three to four times as many stars in the Milky Way field as near the pole. If we repeat the same experiment with a 15-inch telescope the ratio would be more nearly ten to one.

Star clusters generally show preference for the Milky Way. The galactic clusters, of which the Pleiades, Hyades, Praesepe and the double cluster in Perseus are the prototypes, are all found there; all faint galactic clusters lie within a few degrees of the galactic circle. The globular clusters, such as the well-known one in Hercules, act somewhat similarly, though they appear to prefer the regions between five degrees and twenty degrees from the Milky Way circle. The behavior of the nebulae would seem a bit puzzling to the observer with a telescope of moderate size. He would find a good many nebulae such as the Orion nebula or the Carina nebula in the Milky Way, but there are others such as the nebulae in Andromeda or Canes Venetaci at considerable distances from the galactic plane. Observations with large telescopes would straighten out the matter. The diffuse, gaseous nebulae are found almost exclusively in or near the Milky Way. The spiral nebulae—which are in reality galaxies of stars rather than clouds of gas—appear to have a healthy dislike of the Milky Way and evidently prefer the regions at some distance from it. Greek mythology places them without ambiguity among the "common people of the skies"!

There is one further property of the globular clusters that would certainly be noted by a thorough observer with a visual telescope. He would find plenty of globular clusters when our northern "summer" Milky Way is around, but

he would not find many during the winter when Capella is high up in the sky. Our observer would soon come to the conclusion that the globular clusters in their own peculiar way favor one half of the Milky Way. They appear to be particularly fond of the region around Sagittarius, where one third of all known globular clusters are found in an area covering scarcely two percent of the entire sky. Galactic clusters and diffuse nebulae are spread more evenly along the Milky Way.

Photographic Appearance

During the past fifty years most Milky Way research has been done with the aid of photographic telescopes. We shall see in the second chapter the special methods and techniques that have been developed for the attack on Milky Way problems with the aid of photography and spectroscopy. But before we get too serious, we should show you some maps of the route that is to be followed.

Let us start with the composite map of the southern Milky Way at the end of the book. It was made by matching, cutting, and pasting together in true kindergarten fashion a series of black and white prints from photographic negatives made with a 3-inch Ross-Tessar lens of the Boyden Station of the Harvard Observatory in Bloemfontein, South Africa. The photograph covers all the way from the star clouds in Scutum and Sagittarius on the left, past the Coalsack and Southern Cross in the center, to Sirius and the dull homogeneity of Canis Major and Monoceros on the right.

In spite of the small scale, the composite map shows clearly some of the important features to which we have already referred. In some places the resolution is not quite enough to show the individual stars but in general we find here direct confirmation for the stellar nature of the Milky

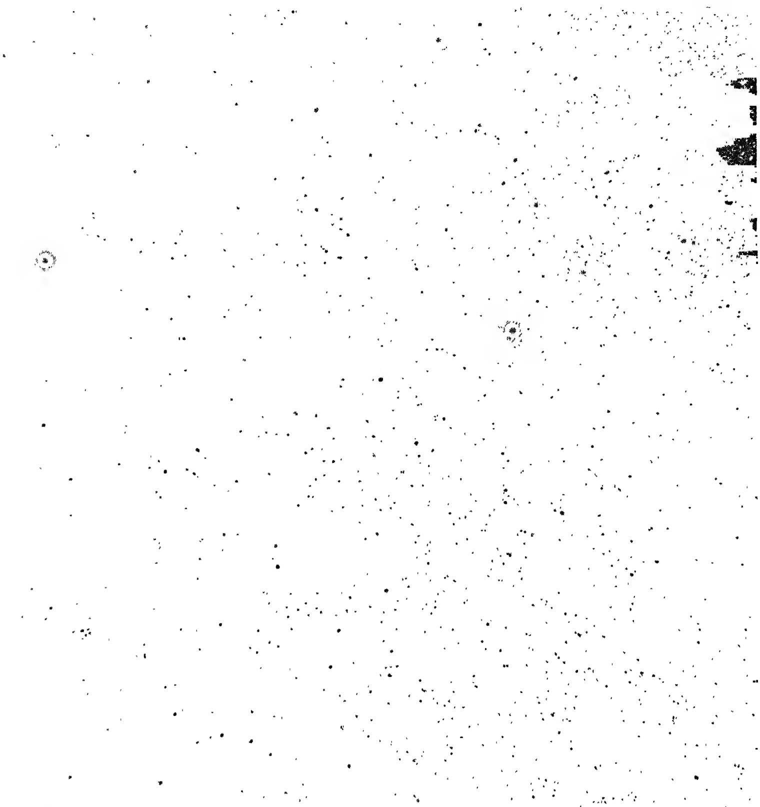

Fig. 2.—The Milky Way in Sagittarius.

From a photograph taken with the 24-inch Bruce camera at the Boyden Station of the Harvard Observatory.

Way. The changing appearance that is noted as we proceed from left to right in the composite photograph is not caused by atmospheric difficulties or differences in exposure time, but is the result of true variations in brightness along the Milky Way. The Milky Way in Sagittarius is very much more spectacular than the Milky Way near Sirius.

The small scale photographs used for the composite map are fine for general survey purposes, but for more detailed studies we need both larger scale and greater penetrating power. As an illustration of the results obtained with telescopes of various openings and focal lengths we reproduce in Figures 4, 5, and 6 three pictures of the diffuse nebula

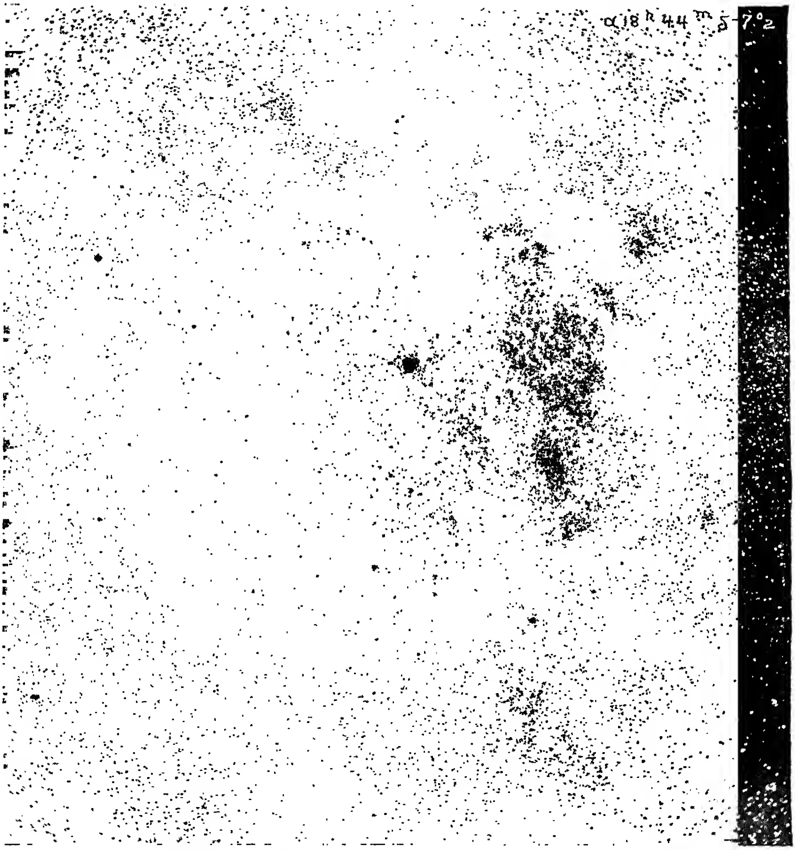

Fig. 3.—The Great Star Cloud in Scutum.

Barnard's "Gem of the Milky Way," from a photograph by Barnard made at Mount Wilson Observatory.

near the southern star Eta Carinae. The nebula can just be seen on the composite photograph on the Milky Way circle at galactic longitude 255 degrees. Figure 4 shows

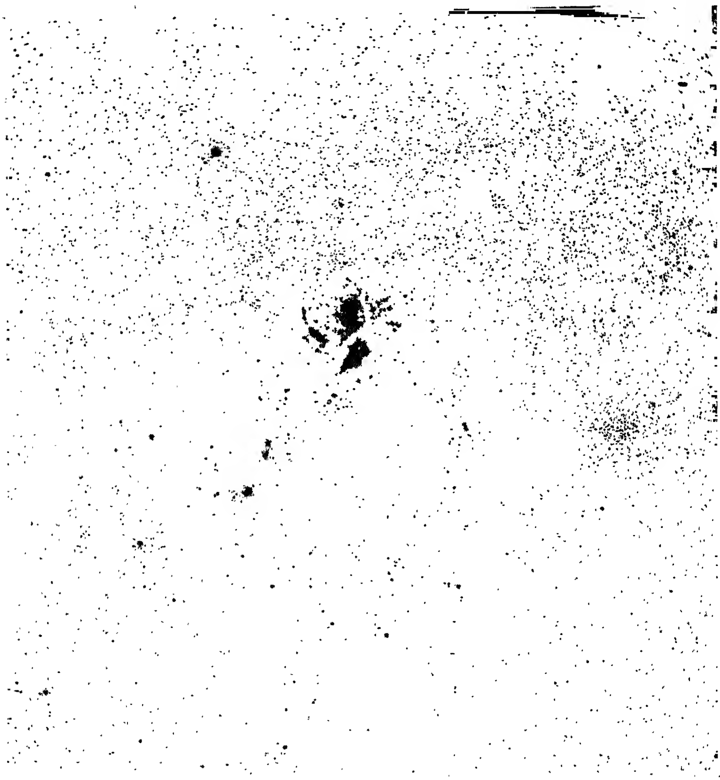

Fig. 4.—The Diffuse Nebula near Eta Carinae.

From a photograph taken with the 8-inch Bache refractor at the Boyden Station of the Harvard Observatory.

how it looks on a photograph taken with the 8-inch Bache refractor, Figure 5 as it appears on a print made from a plate taken with the 24-inch Bruce refractor, and Figure 6 gives the detail revealed by the 60-inch reflector.

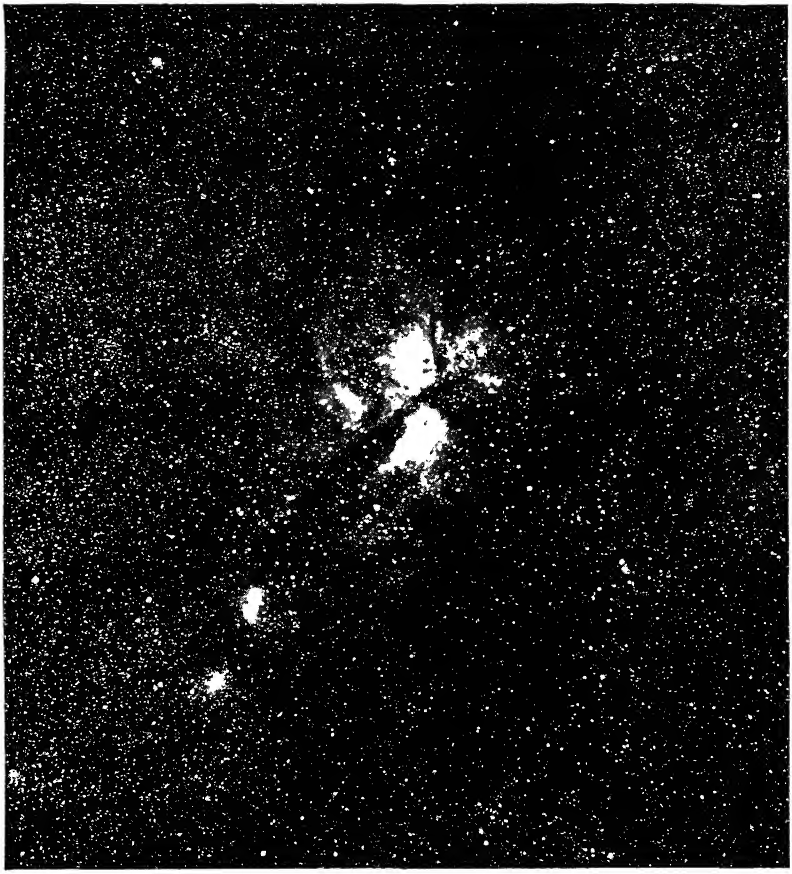

Fig. 5.—The Diffuse Nebula near Eta Carinae.

From a photograph taken with the 24-inch Bruce refractor of the Boyden Station of the Harvard Observatory.

A comparison of these three photographs shows that a larger instrument leads naturally to greater penetrating power and larger scale, but that there is a gradual reduction in the area covered by a single plate as we proceed to the more powerful instruments. The astronomer interested in

Fig. 6.—The Diffuse Nebula near Eta Carinae.

From a photograph taken by Paraskevopoulos with the 60-inch reflector of the Boyden Station of the Harvard Observatory.

Milky Way research is always torn between his conflicting desires for penetrating power and for a larger usable area per plate. The answer to this apparent dilemma may lie in the more effective construction of large instruments. The ordinary parabolic reflector is gradually being replaced by cameras with fast wide-angle lenses, such as those constructed by Ross of Yerkes and Mount Wilson Observatories, and by the fast reflectors with a correcting plate, named after their original designer, Bernard Schmidt, of the Hamburg Observatory. Great advances in Milky Way research may be expected when the large Schmidt cameras that are now under construction swing into action. The Cook Observatory at Wynnewood, Pennsylvania, has in

Fig. 7.—The Milky Way in Andromeda.

From a photograph taken by Ross with a 5-inch camera at the Lowell Observatory.

operation a 10-inch Ross camera, and a 20-inch Ross lens has just been installed at the Lick Observatory. The existing Ross lenses have done very fine work and we can hardly do better than to close our photographic survey with a brief discussion of some "maps" made by Ross with a 5-inch lens and some others made by Tabor at the Cook Observatory.

We have inserted at the end of the book a composite photograph of the northern Milky Way prepared by Struve and Miss Calvert at Yerkes Observatory from Ross' original negatives. The composite reveals beautifully the great sweep of the Milky Way, but the reduction from the originals is too much to make possible the inspection of finer details.

The detailed structure begins to appear in the larger scale photographs. Figure 7 shows the section of the Milky Way north of the great spiral nebula in Andromeda. The nebula itself is an independent Milky Way system outside our own and its occurrence in this photograph is in a way purely accidental. The Andromeda nebula is too far away to have its individual stars resolved on a plate taken with a 5-inch camera (but the 100-inch reflector can do it!) and the single stars in the photograph all belong to our own Milky Way system. There are many more stars near the top of the plate (where the galactic circle lies) than toward the bottom and we have here an excellent illustration of the concentration of stars toward the band of the Milky Way.

Figure 8 is a reproduction of one of Ross' photographs of the Milky Way in Sagittarius, the richest portion of the Milky Way. In some spots the stars are so close together that their individual images have merged into a single diffuse cloud. Photographs with large reflectors, however, show that the stars can be resolved completely in this part of the sky.

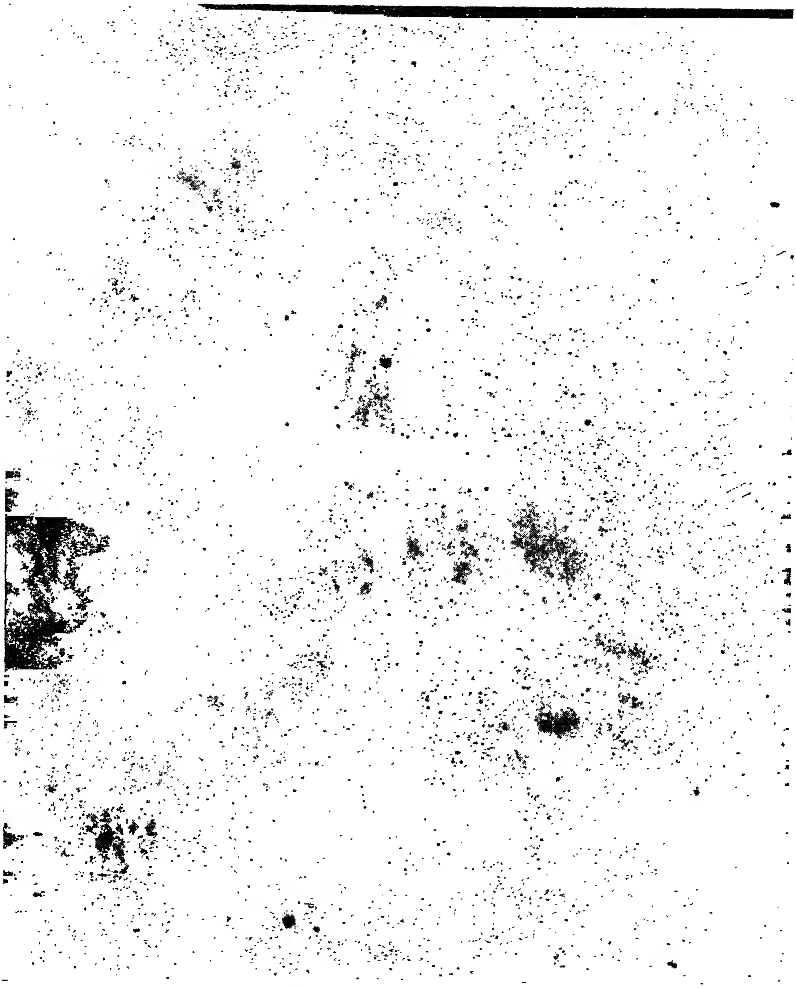

Fig. 8.—The Milky Way in Sagittarius.

From a photograph taken by Ross with a 5-inch camera at the Lowell Observatory.

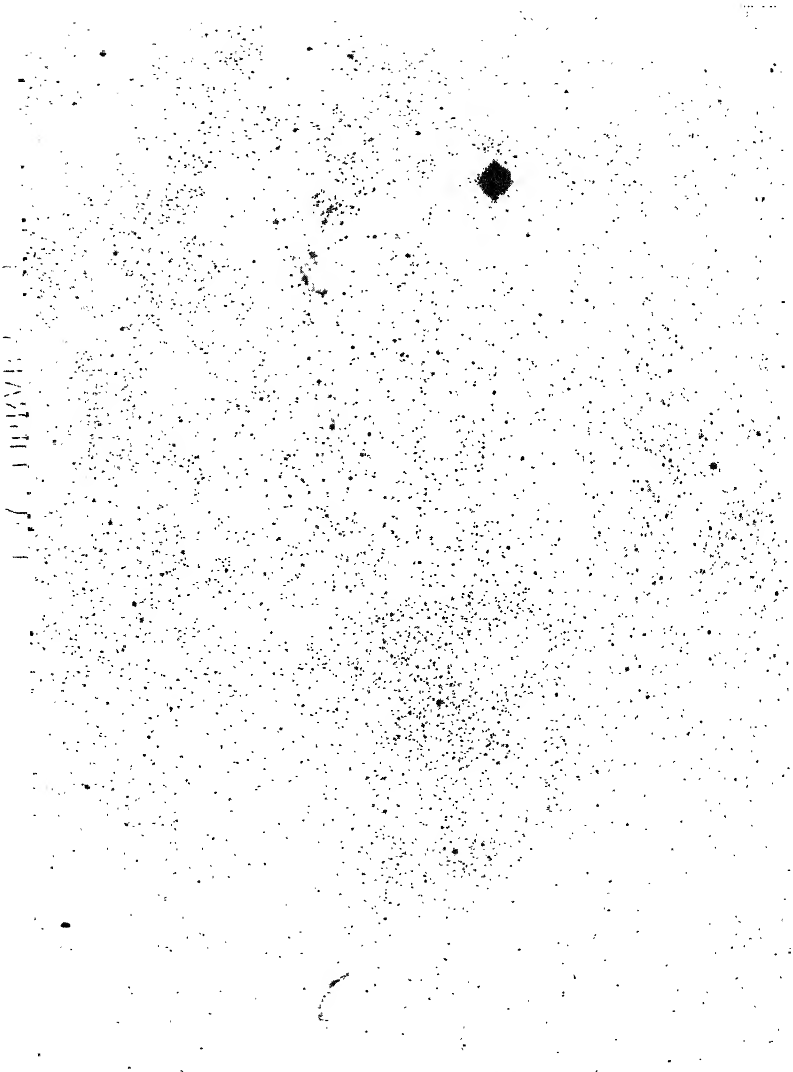

Fig. 9.—The Milky Way in Cygnus.

From a photograph taken by Tabor with a 10-inch Ross camera at the Cook Observatory.

Figure 9 is a photograph taken with the 10-inch camera of Cook Observatory of the Milky Way in Cygnus. It shows the bright star Deneb of the Northern Cross, the North America nebula, the Veil nebula, and the beginning of the Great Rift in the Milky Way. As we compare the different photographs of the Milky Way, we note that every section of the Milky Way has its own characteristics. The Milky Way in Sagittarius bears no resemblance to the Milky Way in Cygnus, which again has little in common with the Milky Way in Carina. A most perfunctory examination of some maps has shown us already that ours is not going to be a dull or monotonous tour.

Our Milky Way System; A Working Model

If this were to be a detective story we might wish to present first all available evidence and then hide the solution in some uncut pages toward the end of the book. Our story is unfortunately not so simple. The evidence is so incomplete in spots that we are nowhere near the final solution for the Milky Way mystery. Under those circumstances we might as well give our "secrets" away at the start. We shall make reading easier by providing a working model of the Milky Way system. The descriptive material of the preceding pages provides already a basis for such a model.

Visual as well as photographic counts have shown that the faintest stars are relatively most concentrated toward the band of the Milky Way. Since, on the average, fainter stars are more distant we have here direct proof that our Milky Way outlines a flattened stellar system. The Milky Way has great depth. Some of the stars that contribute to the Milky Way phenomenon may be only a few hundred light years away, but others are at distances of several thousands of light years from our sun. Since the Milky

Way appears as a great band encircling the sky and cutting it into two very nearly equal parts, our sun must be located close to the plane of symmetry of the system.

Is our sun located anywhere near the center of the system? For many years astronomers believed this to be so, but if you have read carefully through the preceding pages you will find there some indications that it cannot be true. One of the most striking features of the Milky Way is that the half centered upon the starclouds of Sagittarius is wider and more brilliant than the Milky Way in Orion, Taurus, and Auriga. Does this mean that the center of the system lies in the direction of the Sagittarius cloud?

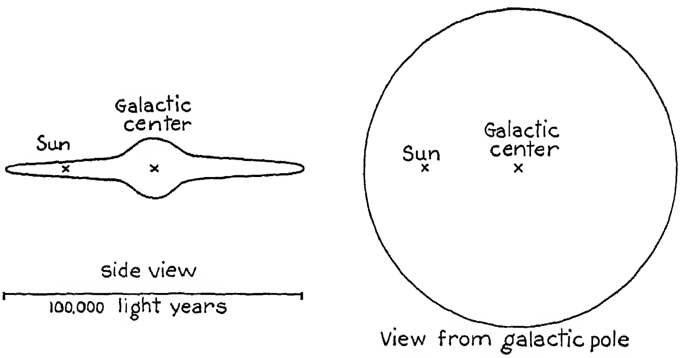

Fig. 10.—Schematic outline of the Milky Way system.

There is much evidence to show that the galactic center lies in the direction of Sagittarius. The globular star clusters exhibit a very pronounced concentration toward the Sagittarius region. Shapley has shown that the globular clusters are among the most distant observable galactic objects; their irregular distribution is strong evidence for the existence of a distant center in Sagittarius. The concentration toward the Sagittarius region is shared by many types of objects that can be observed at large distances from the sun, such as new stars, or novae, distant variable stars and

planetary nebulae. There is finally the evidence from galactic rotation which postulates the existence of a distant center in the general direction of the Sagittarius clouds.

So far we have had no indications of the approximate dimensions of our Milky Way system. The evidence on this point will be presented in due course in later chapters, but we might as well complete the description of our model now. There is fairly general agreement among astronomers that the center of our Milky Way system lies somewhere between thirty and thirty-five thousand light years from our sun.

The working model is shown diagrammatically in Figure 10. There is no such thing as a sharply defined outer boundary of the Milky Way system. The full-drawn line in our diagram is drawn through points where the space density of the stars will hardly exceed a few per cent of the value near the sun. But in later chapters we shall meet occasionally with special stars beyond these boundaries, stars that still belong quite definitely to our own Milky Way system.

What about the motions in the Milky Way system? The system is apparently revolving at a terrific pace around the distant center. This is hardly surprising for the system could not possibly stay as flat as it appears to be without a rapid rotation in the general plane of symmetry. The rate of rotation is fast; our sun is whirled around at a speed of approximately 150 miles per second. That ought to be just about fast enough to suit our readers and should provide enough momentum to propel them through the basic fact-finding chapters that follow, into the realms of fancy.

HOW AN ASTRONOMER ATTACKS THE PROBLEM

OUR EYES ARE OUR FIRST TOOLS. THE SKY LIES OPEN before us, for astronomy is an observational rather than an experimental science. But our eyes are weak and forgetful and therefore we build telescopes, which can gather more light, and cameras, which make permanent records.

One of the obvious questions that we shall wish to answer first is: "How many stars are there?" But even if we can answer this simple question we shall immediately wish to know further how many there are in each successive class of brightness. At once we have met with one of the most difficult problems of the modern astronomer—how to measure accurately the amounts of light that reach us from different stars.

STELLAR BRIGHTNESSES

Since our eyes are the first instrument that we use in our measurements, we should inquire into the simple rules that govern our estimates of brightness. Our appreciation of the difference in brightness of two lights is always a relative

rather than an absolute matter. If we compare two faint stars we can see that they differ appreciably, but bright stars might well differ by the same amount without our being able to detect it, since the difference would be a negligible factor in the total stimulus that we receive. In other words, our eyes estimate ratios of brightness rather than absolute differences.

Hipparchus first divided the naked-eye stars into six classes according to their brightness. Later it was agreed that these magnitude groups should be so taken that the standard first magnitude star (the average of the twenty brightest stars in the sky) gives us one hundred times as much light as a star of the sixth magnitude, which is about at the limit of vision for most people. Since we are interested in ratios of brightness we define a difference of one magnitude as corresponding to a ratio equal to the fifth root of 100, which is 2.512. A difference of two magnitudes corresponds then to a ratio in brightness of $(2.512)^2 = 6.31$, three magnitudes to $(2.512)^3 = 15.85$, four magnitudes to $(2.512)^4 = 39.82$, and five magnitudes to $(2.512)^5$, which is of course equal to 100.

We need perhaps to stop a moment and consider how powerful a geometric factor of this kind can be. Probably you have heard of the man who rashly promised to double his servant's wages every day for a month and thought he had a bargain since the man offered to work for only one cent the first day. The thirty-first day cost him over ten million dollars! So it is with our ratio of brightness. A sixth magnitude star has $1/100$ the light of a first magnitude star; an eleventh magnitude has 1/10,000 the light of the first. With the 100-inch telescope stars of the twenty-first magnitude are reached. Such a star would have $1/(2.512)^{20} = 1/(100)^4$, or 1/100,000,000 the light of a first magnitude star.

If we wish to set up in a certain region of the sky a scale of magnitudes accurate over a large range in brightness, we shall have to take great care to see that the ratio 2.512 is maintained from one magnitude to the next, all along the way. The unaided eye cannot accomplish this and special instruments have been designed for the purpose. We must have some standard source of light; in the meridian photometer of E. C. Pickering this standard was the pole star; in other photometers an artificial star is used. There must be some means of cutting down the light of the brighter star by a measurable amount. This can be done either by a polarizing device or by a wedge. With his meridian photometer Pickering made over a million observations to determine the relative magnitudes of the brighter stars of the sky.

Fig. 11.—Edward C. Pickering of Harvard.

It is not possible, even with large telescopes, to extend our scale of magnitudes to faint stars by purely visual methods. The visual method has the further disadvantage that all measurements must be made at the telescope, and it is not surprising that in this field, as in many others, astronomers have made use of photography.

The regular photographic plate is more sensitive to blue and violet light than is the eye. This means that two stars of different color might appear the same to a visual observer, but the bluer one will appear brighter on a photographic plate. For this reason it will be necessary to set up a whole separate scale for photographic magnitudes which will

differ from the visual scale by amounts dependent on the colors of the stars.

How are we to compare the total amounts of light that two stars of different brightness contribute to the photographic plate? The stellar images will differ in size and in intensity. In order that they shall appear equal it will be necessary to cut down the light of the brighter one by a known amount. We might do this by shortening the exposure time, but if we use that device we must first study the photographic plate to determine the exact relationship between length of exposure time and intensity of images. We can also cut down the amount of light by placing a diaphragm over the objective of the telescope. The light gathering power of any telescope varies as the area of the objective so that we can measure exactly by how much we reduce the light of any star. We again select some star as our standard and take an exposure with the full aperture of the telescope. Next we must find what proportion of the aperture we must use so that, with the same exposure time on the brighter star, we obtain a photographic image identical in appearance with the standard. The ratio of the total area of the reduced and full apertures measures the ratio between the brightnesses of the two objects.

Fig. 12.—Frederick H. Seares of Mount Wilson.

It is largely through the efforts of Pickering and Miss Leavitt at Harvard, and Seares at Mount Wilson, that we possess today, in the region around the North Pole, two

very reliable standard sequences of stellar magnitudes, the one visual, the other photographic. It seems very unlikely that either scale could be wrong by as much as one tenth of a magnitude from the first to the eighteenth magnitude.

During recent years photographic technique has made such rapid strides that purely visual work on standards of magnitudes has practically been eliminated. We now have yellow sensitive plates, which give magnitudes on the photographic plate which will match those given by direct visual observation. These are called photovisual magnitudes.

The standard sequences at the North Pole are always available to observers in the northern hemisphere. On any clear night they can be photographed at the same time and under the same conditions as the field for which the astronomer wishes to determine photographic or photovisual magnitudes.

Stellar Colors

The color of a star is determined by the difference between its photographic and its photovisual magnitudes. By general agreement, the two scales of magnitudes have been so adjusted that a white star, such as Sirius, will have the same magnitude in both scales. The difference, photographic magnitude minus photovisual magnitude, is called the color index of a star. For very blue stars, such as Rigel, it will be a negative quantity since such stars appear brighter on the ordinary photographic plate than on the yellow sensitive plate. The color index increases to plus two or three magnitudes for the very red stars, such as Betelgeuse. This color measure is also a measure of the temperature at the surface, the blue stars being hotter than the red ones. Since color indices are fairly easy to obtain, and can be found even for extremely faint stars, they are of great value in studies of the distribution of the stars in

Fig. 13.—The Southern Cross in blue and red light.

Two Harvard photographs of the region of the Coalsack and the Southern Cross. On the top is a photograph in red light, on the bottom one in blue.

space. We shall see in later chapters that the light of distant galactic stars is appreciably reddened by interstellar light scattering. The color index of a distant star of known spectral class will then prove to be a measure for the total amount of scattering material in the space between our sun and that particular star.

Until ten years ago measures of stellar colors were made almost exclusively by a comparison of photographic and photovisual magnitudes. Other magnitude systems have since come into use. When the manufacturers of photographic plates were able to prepare stable, and yet "fast," emulsions that were sensitive to red rays, astronomers decided to set up a photo-red system of magnitudes. Dr. and Mrs. Gaposchkin at Harvard set up a standard sequence, again for the region of the North Pole. Figure 13 shows a comparison between a blue and a red view of the region of the Southern Cross.

It is very difficult to obtain from photographic plates magnitudes that are accurate to within three per cent. If very high accuracy is desired the photo-electric cell has decided advantages. Colors of faint stars can be determined photo-electrically by comparing the galvanometer or electrometer deflections when the star's light is allowed to pass successively through filters, sensitive to different colors. The method has been perfected for work on faint stars by Stebbins and his associates at Wisconsin and Mount Wilson. The relative error of a good photo-electric color index is less than one per cent.

Spectral Classes

The modern astronomer would feel lost without his spectroscopic tools of research. Large prisms, that can be placed in front of the objectives of photographic telescopes, are standard equipment at many observatories. Figure 14

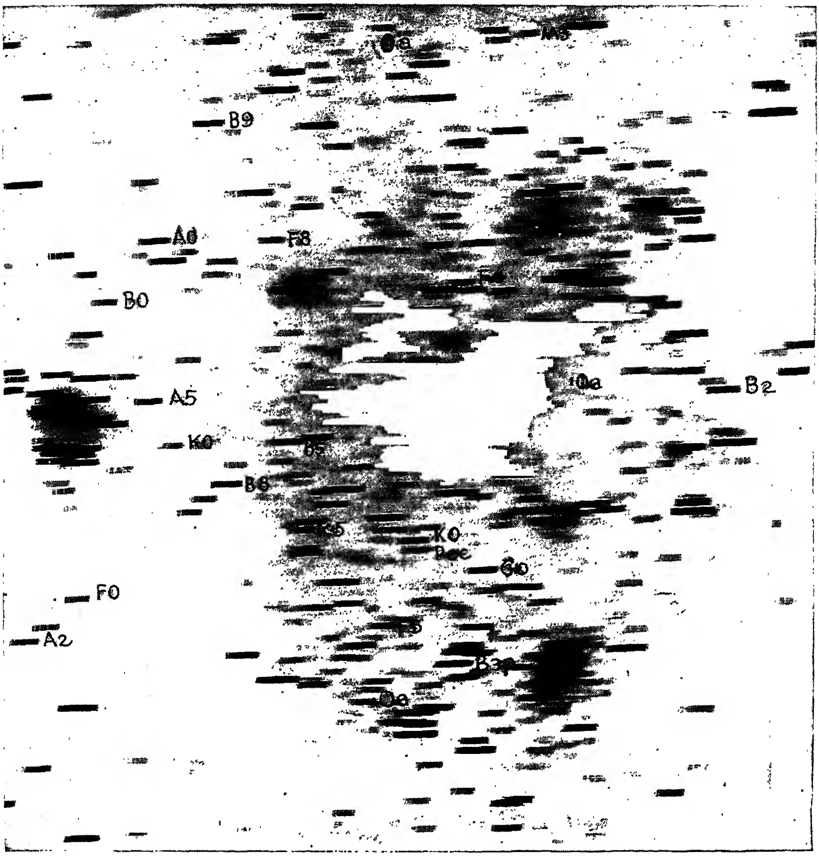

Fig. 14.—Stellar spectra with the objective prism.

Stellar spectra classified at Harvard from a plate taken with an objective prism placed in front of the lens of the telescope. The spectral classes are indicated for some stars.

shows the kind of photograph that is obtained with the prism attached. The stellar spectra appear generally as little bands, crossed by dark lines, the so-called absorption lines. But even the most cursory inspection shows that all

spectra are not alike. The "Balmer" lines of hydrogen are strong in some spectra, weak in others, and totally absent in still other spectra. The lines of iron and other metals are sometimes present and in some spectra molecular bands are the outstanding feature. These differences were a challenge to the astronomers of the gay nineties as they began to sort out the various spectral characteristics. It was soon clear that the stars could be sub-divided into a fairly small number of classes which merged gradually one into the next.

The classification in use at present was worked out at the Harvard Observatory under Professor Pickering by Miss Cannon, Miss Maury and Mrs. Fleming. The Henry Draper Catalogue is the work of Miss Cannon and contains the spectral classifications of 225,320 stars, of both the northern and southern sky, including practically all stars to between the eighth and ninth magnitudes. The Henry Draper Extension, which is still less than half done, continues the classification to the eleventh magnitude. The classes were first lettered in alphabetical order, but by a "survival of the fittest" the sequence of classes has narrowed down to *O-B-A-F-G-K-M*, with in addition a few odd stars of classes *R-N* and *S* and some individuals craving for notoriety that are labeled "Pec" for peculiar. On Figure 14 the spectral classes of some typical stars have been marked beside their spectra.

Fig. 15.—Annie J. Cannon of Harvard.

A line-up of characteristic stars in this *O-B* to *M* sequence is also, very strikingly, a line-up in color. The *B* stars are blue stars such as Rigel and other stars in Orion; the *A* stars with Sirius and Deneb as examples are white; Procyon and Capella give us examples of the *F* and *G* type and appear yellow; finally we come to the orange and red *K* and *M* stars with Arcturus, Aldebaran, Antares and Betelgeuse. When the spectra are arranged in this same order we see also the shift in maximum intensity from the violet end of the spectrum to the red. This is an indication that the temperature is decreasing as we pass through the spectral sequence. The place of a star in the sequence is determined by its surface temperature rather than by its chemical composition. The chemical composition is believed to be the same for all except a small minority of the stars, but the conditions of temperature and pressure at the star's surface will make great differences in the spectral lines which appear.

The *O* stars are the hottest stars, some with surface temperatures as high as 100,000°C. Their spectra can easily be recognized on the photographs by the presence of certain characteristic bright lines (an exception to the rule!) or by the extension of the background far into the ultraviolet. The *B* stars, which are still quite hot (25,000°C. at the surface) and blue, follow directly upon the *O*'s. Their spectra show the lines of helium and hydrogen. Helium fades out and hydrogen strengthens as we approach class *A*. Lines of calcium and metals, such as iron and magnesium, gradually increase in strength through classes *F* and *G*; our sun is a typical *G* star. In class *K* the calcium lines become very strong and bands due to molecular compounds come into view. Class *M* are the red stars, with temperatures of less than 3000°C., the spectra showing bands of titanium oxide. The symbols *R*, *N* and *S* refer to a parallel

branch of cool stars in whose spectra other molecular compounds are present.

To expert classifiers there is still much difference between a "cool" *B* star and a "hot" *B* star. A careful system of classification distinguishes several subclasses. The hottest *B* star is called *B*0, one with a medium temperature *B*5 and the coolest *B* star is classified as *B*9. The *A*0 stars follow directly upon the *B*9 stars.

Distances and Parallaxes

When we see stars in the sky that differ so much in brightness we are naturally curious as to how much of this difference is real and how much is due to the varying distances from us. If light travels unobstructed through space its brightness varies inversely as the square of the distance from the source. With our scale of magnitude, if two stars differ apparently by five magnitudes (which means a light ratio of 100 to 1), but are actually equally luminous, the fainter one must be ten times as distant. How can we find the distances of the stars and so discover how much of the range in apparent brightness is due to distance and how much is due to variations in intrinsic brilliance?

The astronomer's method of finding the distance of a star is essentially the same as that of a surveyor who measures the width of a river. He measures carefully along the bank as long a base line as possible. At either end he measures the angular direction along which he sights on some tree or land mark on the opposite shore. This gives the angle-side-angle well known to high-school geometers as enabling them to compute any other part of triangle. The astronomer likewise has to have a carefully measured baseline and then the exact direction angles along which he sees the star. To get a long enough base line for the great

distances of the stars is impossible on our tiny earth. But our earth moves in a great circle about the sun. If he will but wait six months after one pointing he will have moved, without any effort on his part, 186,000,000 miles, or twice the distance from the earth to the sun.

From the two ends of his base line he can sight on his star and he will find that at least the nearest ones have shifted slightly their positions with reference to fixed direction lines, or better still, with reference to the background of more distant stars. Even for the nearest star the measurements are difficult; it is still as though we asked the surveyor to measure from two points a yard apart the shift in direction of a point 145 miles away.

The astronomer uses as an indicator of distance the shift in apparent position of the stars, which is the quantity that is actually measured, rather than the distance expressed in miles, kilometers or light years. The astronomical unit—the distance from the earth to the sun—is the base line for our celestial triangulations. The corresponding angular shift is called the parallax of the star. The parallax equals therefore the angle subtended by the radius of the earth's orbit as viewed from the star.

It is not difficult to change from the parallax to the distance of a star. To do so we introduce a new unit of distance to which has been given the hybrid name "parsec." A star at the distance of one *par-sec* will have a *par*allax of one *sec*ond of arc. The distance in parsecs is equal to the reciprocal of the parallax in seconds or $d = 1/p$. The distance of one parsec is equal to 206,265 astronomical units, or 206,265 $\times$ 93,000,000 miles = 19,000,000,000,000 miles. Instead of the parsec we shall use mostly the more picturesque unit, the light year. The light year is the distance that light travels in a year. At the rate of 186,000 miles a second, and with slightly more than 31,500,000

seconds in one year, the light year is equal to 5,800,000,-000,000 miles. Therefore one parsec is equal to 3.26 light years. The nearest star has a parallax of 0.76 seconds of arc or a distance of 1/0.76 parsecs = 1.32 parsecs. Light takes over four years to reach us from our nearest neighbor. Isolationism is a term that means something when applied to the stars!

Finding the parallax of even one star is an exacting and time-consuming process. Photographs must be taken with a long-focus camera so as to have a large scale. These photographs must be repeated as exactly as possible at several six months intervals. If the parallax star is much brighter than the companion stars there must be some method of cutting down its light. It is impossible to measure accurately images which are of very different sizes and densities. Directly measured parallaxes are available for some few thousands out of the many millions of stars. Even with the best equipment and the greatest care the astronomer cannot measure an angle smaller than $0''.005$. This carries us out only to 200 parsecs or 650 light years. A parallax observer must often wish he inhabited Jupiter with an orbit five times the diameter of that of the earth or Pluto which would give him a still longer base line on which to sight at the distant stars. But when human beings are thwarted in one direction they become more ingenious in finding ways out of their difficulties. Many clever ways have been devised for solving this problem of finding distances which cannot be measured by direct means.

But before we get too far out into space let us first see what results can be found from direct parallax measurements.

Absolute Magnitudes

If we know the distance of a star, and also how bright it appears to us, we can find its true or intrinsic brightness.

We may then compare the intrinsic brightness of each star with that of our sun. Or we may imagine all stars placed at the same standard distance and compute, from the observed apparent magnitude and known distance, how bright the star would have appeared if placed at the standard distance. We call this magnitude the absolute magnitude of our star. International amenities force us to choose ten parsecs as the standard distance. The formula for the computation of the absolute magnitude M is:

$$M = m + 5 - 5 \log r,$$

or, absolute magnitude is equal to the apparent magnitude plus five minus five times the logarithm of the distance in parsecs. Altair with a measured parallax of $0''.2$ has an apparent magnitude $m = 0.9$. Since its distance is $1/0''.2 =$ five parsecs, its absolute magnitude becomes:

$$M = 0.9 + 5 - 5 \times (0.70) = +2.4^*$$

When we arrange all the stars at the standard distance we find that the stars show as wide a range in absolute magnitude as they do in apparent magnitude. There are stars all the way from -5 or -6 to $+12$ or $+14$. We can set the sun in imagination off at this standard distance and we find that its absolute magnitude lies near the middle of

* To derive this equation will be fun for those who are used to logarithms and remember how we defined magnitudes.

l = apparent brightness of star
L = absolute brightness of star

$$\frac{l}{L} = \frac{(\text{standard distance})^2}{(\text{actual distance})^2} = \frac{(10)^2}{r^2} \text{ in parsecs} = (2.512)^{M-m}$$

Taking logarithms:

$$0.4(M - m) = 2 - 2 \log r,$$

or

$$M = m + 5 - 5 \log r.$$

the range at +5.0. If we wish we can compare all the stars to the sun as the standard—the standard candlepower as it

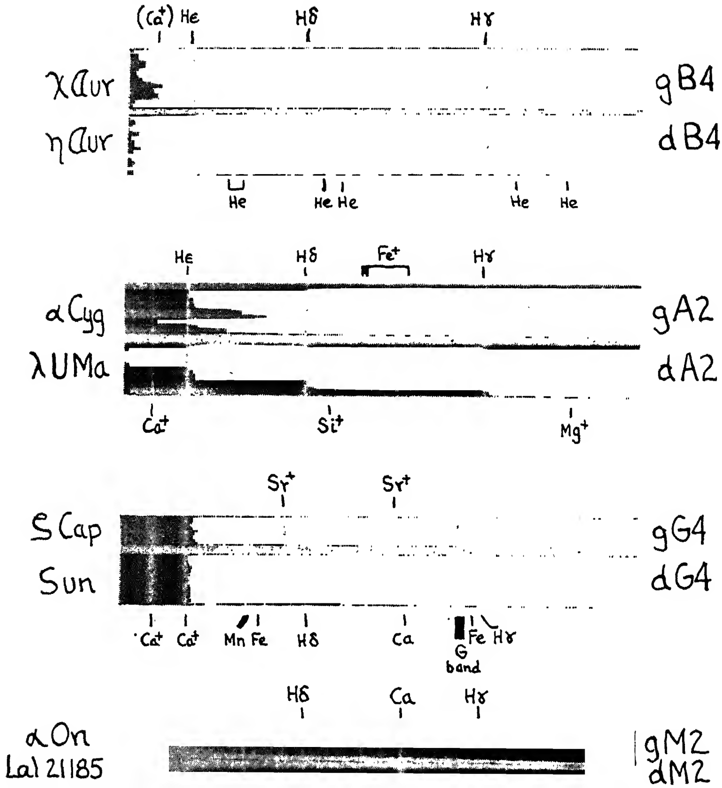

Fig. 16.—Spectra of giants and dwarfs of various spectral types. The lines marked above each pair show considerable differences between giants and dwarfs. Some of the other strong spectral lines are marked below each pair. The Ca^+ line in Xi Aurigae is of interstellar origin. Spectra taken by Morgan at Yerkes Observatory.

were—and we obtain what is called the relative luminosity of the stars. A difference of 15 in the absolute magnitude will make a difference of $(2.512)^{15}$ or 1,000,000 in the actual

amount of light the stars are emitting. Where there are such tremendous differences from one star to another it is unsafe to guess whether a particular star is faint because of its low luminosity or because it is very far away. On the average the fainter ones will be more distant, but we cannot say anything about the distance of any one particular star unless we know something more than its apparent magnitude.

Fig. 17.—Walter S. Adams of Mount Wilson.

Fig. 18.—Arnold Kohlschütter of Bonn.

We shall see in Chapter 3 that there is a wide range in absolute magnitudes for stars of most spectral types. Capella, for example, has a spectrum very much like that of our sun, but its absolute magnitude is −0.4 which means that Capella is 5.4 magnitudes brighter than (or 150 times as bright as) our sun. Are there no differences in spectral characteristics between the giants and dwarfs of the same spectral class? Figure 16 gives the answer. There are some differences, but it takes spectra of high quality to find them.

If we have spectra, such as those in Figure 16, we can go a step beyond straight classification and estimate from the spectrum directly the approximate absolute magnitude of the star. We can then find the star's distance by re-writing the formula for the absolute magnitude in the form:

$$5 \log r = m - M + 5,$$

and find the star's so-called "spectroscopic parallax" from the equation

$$p = \frac{1}{r}.$$

The investigations of Adams and Kohlschütter at Mount Wilson in 1914 laid the foundation for our modern researches on spectroscopic parallaxes. We can frequently obtain more reliable data on a star's distance from purely spectroscopic estimates than from careful direct measurements.

Proper Motions

In 1718, Halley compared the positions of Arcturus and Sirius as he saw them then with the positions given in the catalogue of Ptolemy. They had moved considerably from the positions measured by Ptolemy. The so-called "fixed" stars are not stationary but are all shifting their positions continuously on the sky.

Figure 19 shows the motion of the star with the largest known proper motion. This star, called Barnard's star after its discoverer, moves at the rate of 10 seconds of arc a year. When two photographs taken a year apart are superimposed, as in Figure 19, the "runaway" can at once be spotted among the other stars.

Most stars move much more slowly, so that a longer interval of time is necessary for their detection. Accurate observations of position in the sky are made with the

meridian circle. The observations are repeated at later dates and the positions are compared. The amount of the motion increases with time, so that if ten or twenty years

Fig. 19.—A fast-moving star.

Two photographs of Barnard's star, taken eleven months apart with the 24-inch refractor at Sproul Observatory, have been combined to show the effect of the annual displacement caused by the proper motion of this star.

does not suffice to show a measurable quantity, fifty or one hundred years should do the trick.

For the faint stars it is usual to work with large numbers on photographs instead of individually with visual measurements. Suppose we have two photographs of the same part of the sky taken with the same telescope some twenty or

forty years apart. If the scale of the plates is large enough we can measure the positions of the stars to the hundredth part of a second of arc. The difference between the two positions can be reduced to proper motions if there are enough stars with well known proper motions on the plate.

For all the bright stars and a great many faint ones, the proper motions are now known fairly accurately. The Boss catalogue of proper motions, prepared at the Dudley Observatory in Albany, gives the proper motions of some 33,000 stars. This list includes all the stars brighter than the seventh magnitude and many fainter stars of special interest. These proper motions have been obtained by meridian circle observations. There are also catalogues of photographically determined proper motions such as the Yale and Cape Zone catalogues.

For a star whose proper motion and distance are known it is possible to translate the angular value of proper motion into a linear value of miles or kilometers a second. The normal or average velocity of the stars is about twenty kilometers a second. Furthermore there is little range in this value—the extremes being a few kilometers a second up to a possible one hundred or very rarely higher. The velocity of the majority of stars lie close to the average value. Since all the stars are actually moving at about the same rate in space, the proper motion becomes a fairly good criterion of distance.

In one of his short stories Poe tells of a moment of horror when he mistakes a bug crawling on the window pane for a strange monster moving rapidly across the hillside which was in the line of sight. The astronomer may in the same way be fooled and mistake a slow moving neighbor for a distant speedy star. On the average, however, a large proper motion is a good indication of closeness and such stars are at once placed on a parallax observing program.

We have seen that most stars are too distant for parallax determinations and that the measurements are too costly of time and effort to be wasted on objects which will not give us a measurable value. Proper motion gives us a quantity which, on the average, increases as distance decreases and so sorts out the few within reach of our measuring rod from the vast numbers which must be gauged by other methods.

To select the faster moving stars for direct parallax measurements the astronomer has an ingenious method known as "blinking." Two plates of the same region taken some years apart are so arranged that first one and then the other is viewed through an eyepiece. When the alternation takes place quickly enough the background of stars appears to remain the same but the stars which have a large motion will apparently "hop" on the plate. These stars can be marked and later their positions can be measured. In this way all the southern sky and much of the northern has been viewed and all the faster moving stars sorted out and measured. This method enables us to pick out our nearest neighbors from the general run of stars. In Chapter 3 we will see how very useful it is select our neighbors and find just how crowded our particular part of space is.

Radial Velocities

If the stars are moving in space some must be getting closer, others farther away from us. Proper motion cannot tell about this component of the motion since proper motion is the projection of the space motion on the plane of the sky. If we wait for the stars to grow brighter or dimmer as they move closer or farther away, we should have to wait for more than a hundred years before we could measure a change in even the nearest stars. A change in the proper motion of a star is also a very small amount and only observable in very rare instances.

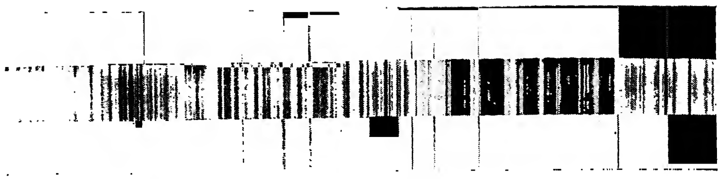

Fig. 20.—The effect of radial velocity.

The spectrum of the bright star Alpha Centauri with an iron spark comparison spectrum on either side. The shift in wavelength caused by the star's radial velocity is clearly shown. Spectrum from Lick Observatory.

Since light is a wave motion it is not surprising that it has some of the characteristics of sound, which is a wave motion of the air. We all have noticed how the pitch of a locomotive whistle changes as it passes us—growing lower as it moves away. In the same way the waves of light are crowded together as the star approaches us, causing the absorption lines in the star's spectrum to be shifted toward the violet. When it recedes from us the lines are shifted toward the red. The amount of the shift in wave-length is directly proportional to the speed of the stars in miles. We have the very simple equation:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

where λ is the observed wavelength in the spectrum of the star, λ_0 the laboratory standard wave length, v the velocity of the star, and c the velocity of light (300,000 kilometers per second).

How do we measure the shift in wave-length for a given star? Figure 20, which is a reproduction of the spectrum of Alpha Centauri taken at the Lick Observatory, shows the stellar spectrum with a laboratory standard on either side. The displacement, which can readily be seen by direct

inspection of the photograph corresponds to a radial velocity of approach of 37.1 kilometers per second.

Much of the early exact radial velocity work was done at the Lick Observatory with the 36-inch telescope and the three prism Mills spectrograph by Campbell, Wright and Moore. The Lick catalogue of radial velocities now includes almost all the naked eye stars in both hemispheres.

One complication which slows down the measurement of radial velocities comes from the fact that many of the stars are found to have velocities that change with time. They are double stars moving about each other under the law of gravitation. These double stars are very interesting in themselves and give us much information about the masses of the stars, but they do not speed up the job of finding the radial velocities of all naked eye stars. For such double stars enough plates must be taken to find out how much of the observed speed is due to the orbital motion, and how much to the speed of the system.

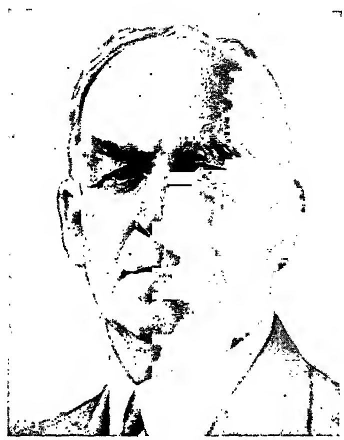

Fig. 21.—William Wallace Campbell of Lick Observatory.

Recent instrumental developments have speeded up the work on spectra of fainter stars. Mirrors are now covered with aluminum instead of with silver, to reach further into the ultra-violet, more transparent optical glass can be used for prisms, and gratings can be made which concentrate most of the light in one spectrum. Cameras of the Schmidt type and new high speed photographic emulsions all will help to reach fainter stars so that we can find the speeds

with which they are traveling and build up our picture of the motions of the whole system.

It is also possible now to take group photographs which will show the speed of many stars instead of each star having to have an individual sitting. To do this a prism is placed in front of the lens, just as in the method that has long been used for spectral classification. A comparison spectrum with zero speed must be inserted so that the displacement can be

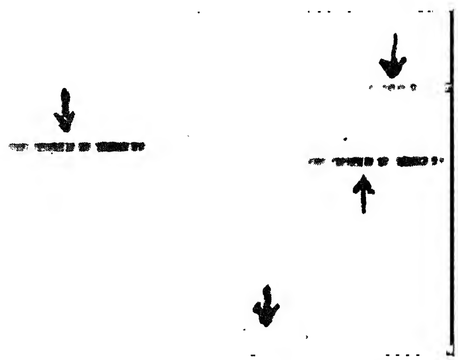

Fig. 22.—Radial velocities from objective prism spectra.

A small portion of a plate used for the measurement of radial velocities from objective prism spectra. The arrows indicate the absorption lines from neodymium chloride.

accurately measured. For some stars, a screen of neodymium chloride which gives dark lines in the spectrum at known positions serves as the standard comparison. Figure 22 shows an enlarged portion of a plate used for the measurement of radial velocities from objective prism spectra. The arrows mark the position of the sharp band produced by the solution of neodymium chloride, which is placed directly in front of the plate. The radial velocity shifts can be determined from the measured distance between the stellar lines and the neodymium band. The method yields results of

not too high accuracy, but it makes it possible to reach faint stars en masse.

Cooperation in Research

The gathering of data of observation that are to serve as a basis for a first attack on the problems of the Milky Way is no small task. It is not so much that the making of a single observation, or a reasonably small number of them, presents any special difficulties, but the trouble lies in the large numbers involved. A Milky Way astronomer of the nineteen forties, who could write his own ticket, would like to have available for analysis the spectral types and colors of two million stars, starcounts to faint limits totaling roughly twenty million stars, proper motions for half a million and radial velocities for one hundred thousand. He would probably wish to have also ten thousand trigonometric parallaxes, spectroscopic parallaxes for one hundred thousand objects and quite extensive data on the distribution of galaxies, variable stars, clusters, novae, and a host of special objects. In addition he would constantly be clamouring for higher precision; so you can have some idea of the magnitude of the task that faces astronomers today.

It is small wonder that under those circumstances astronomers have felt the need for intensive cooperation and joint planning. During the past twenty years the International Astronomical Union has been the most effective clearing house for research plans, and the standing committees of this organization have initiated many cooperative schemes for research.

The need for international cooperation was, however, felt long before the founding of the I.A.U. One of the first efforts was the Great Map of the Sky, or, as it is more commonly known, the Astrographic Catalogue and Charts. The scheme was launched at an international conference

held in Paris in 1887. The plan was to procure a complete photographic chart of the heavens that would reach to the thirteenth or fourteenth magnitude at least, and be as accurate as possible. Eighteen different observatories co-operated in the scheme. Many volumes of the Astrographic Catalogue have already appeared in print, but these have unfortunately not proved too useful for Milky Way research, partly because most of the effort went into obtaining accurate positions (which are of little direct use) rather than into the all-important work on photographic magnitudes.

Two early schemes that have been far more effective are the work on the catalogues of the Astronomische Gesellschaft, begun in 1863, and Kapteyn's Plan of Selected Areas dating from 1906.

Fig. 23.—Frank Schlesinger of Yale.

The work for the catalogues of the Astronomische Gesellschaft involved the accurate measurements—with the aid of a meridian circle—of the positions of the stars of the ninth magnitude and brighter. The undertaking was ambitious, but much less so than that of the Astrographic Catalogue. The A.G. catalogues have for many years been standard references in observatory libraries. In the United States the Naval Observatory, the Harvard Observatory and the Dudley Observatory each undertook the measurement of positions in one of the A.G. zones.

In recent years the positions of stars in the A.G. zones have been re-determined by Schlesinger at the Yale Observ-

atory and through a cooperative plan of German observatories. In the repetition use was made of a photographic technique for the measurement of positions. The wide-angle cameras, to which we have already referred in the first chapter, have proved exceedingly effective in this work. Accurate proper motions are being derived for all stars for which both early and late positions are available.

Fig. 24.—Jacobus C. Kapteyn of Groningen.

The A.G. stars for which proper motions are available can serve more effectively in Milky Way analysis if their apparent magnitudes and spectral types are known as well. The magnitude job is being handled effectively at Rutherfurd Observatory at Columbia and the spectra have been determined by Miss Cannon at Harvard. The A.G. work does not reach stars south of declination −23°. A similar study of positions, proper motions and magnitudes has however been undertaken at the Cape of Good Hope for the zone of −40° to −52°; again Miss Cannon was called on for the classification of the spectral types.

Kapteyn's plan of Selected Areas represents probably the most famous cooperative scheme of all. Kapteyn realized that it was necessary for a first attack on the problems of the Milky Way to know as much as was humanly possible for a relatively small number of special, selected regions. He chose 206 regions evenly distributed over the sky and requested that astronomers everywhere cooperate in the

determination of magnitudes, spectra, proper motions, etc., for those regions.

Kapteyn's Selected Areas have already figured prominently in many galactic investigations and the work is by no means done. For the Areas north of $-15°$ the photographic

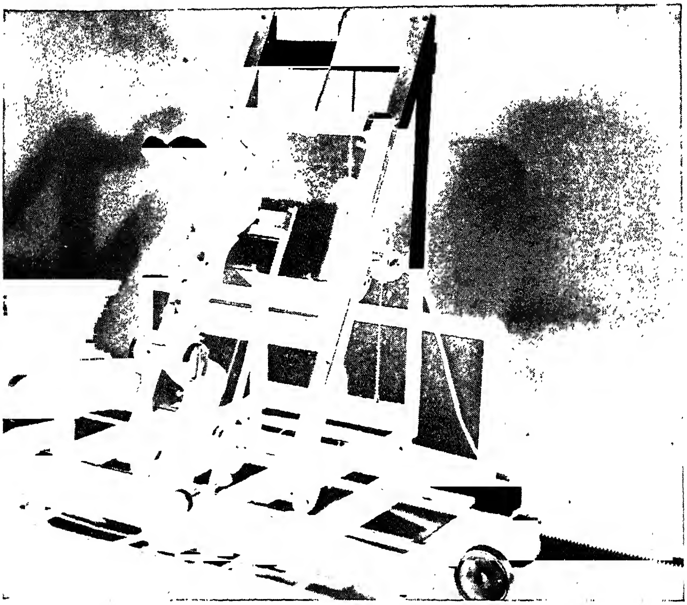

Fig. 25.—Machine used for magnitude measurements and star-counts.

The plate, together with the artificial scale, are viewed through a low-power binocular microscope. Vassar College.

magnitudes are known through the cooperation of the observatories of Mount Wilson, Groningen (Holland) and Harvard. The magnitudes of the stars in the Areas south of $-15°$ are urgently in need of further attention and plates for this work are accumulating at Harvard's station in South Africa. The German observatories in Potsdam and Ham-

burg have classified the spectra of 150,000 stars in the southern as well as northern areas. The Radcliffe Observatory in Oxford, England, has issued a catalogue of proper motions for the northern areas; the Mount Wilson and David Dunlap Observatories are working on radial velocities; research on colors of faint stars is being done at Mount Wilson and Harvard. Kapteyn's Plan of Selected Areas is a going concern if ever there was one!

During recent years a different type of cooperative research has come forward. The Harvard Starcounting Circuit is a good example of this type of development. When it became necessary to obtain complete starcounts for the entire Milky Way down to the fifteenth magnitude, it was clear that this could hardly be undertaken by one single observatory. Astronomers at many observatories offered to cooperate by each counting and analyzing a different section of the Milky Way. At the time of writing, this circuit includes Denison University (Cygnus, Aquila), Case School (Taurus, Orion), the University of Illinois (Cassiopeia, Auriga), Randolph Macon Women's College (Cepheus) and Mills College (Perseus) in the United States. Foreign observatories that are cooperating are the Armagh Observatory in Northern Ireland (Ophiuchus, Sagittarius, Southern Coalsack) and the new observatory in Tonanzintla in Mexico (Puppis, Vela). The Harvard astronomers are working on the sections in Monoceros, Carina, and Centaurus.

No astronomer need feel frustrated because of lack of suitable equipment. There is always somewhere a useful cooperative scheme in which there is enough glory for all, and in which any eager worker is welcome.

3

THE SUN'S NEAREST NEIGHBORS

*H*OW DOES THE SUN RATE AMONG THE OTHER STARS? Is it very brilliant, is it average, or somewhat dull? As students of the Milky Way we are interested in the answers to these questions, not so much because we care about the sun itself, but because we wish to know what variety exists among the stars and just what proportions there are of the different kinds in an average sample of space.

This situation is analogous to that of a sociologist who wishes to make a study of the population of some large city, such as Boston and its suburbs. It would be beyond his capacity to make a door-to-door census of the whole community but he could at least select a few sample areas for a complete census. With care he could in this way probably obtain a fair estimate of the average citizenry. The chances are that he would not include a single college president or mayor and he would be almost certain to miss the governor of the state. If he is eager to include in his survey the extremes, he will supplement his daily house to house canvases with the study of some newspaper, say the now defunct Boston Transcript. This will acquaint him with the

frequency of celebrities and queer ducks in the community. If our man were a good sociologist he would combine in his final report the statistics from the door to door census with an analysis based on his daily readings in the Boston Transcript.

For the stars, a list of nearest stars corresponds to the door-to-door census; a list of brightest stars tells us of those that are unusual but which, because of their brilliance, can be observed at great distances. They get into the papers!

The Brightest and the Nearest Stars

We shall consider here two lists of stars that have recently been published by van de Kamp of Swarthmore. Table 1 is a list of the brightest stars in the sky. Table 2 is a list of the stars that are known to be within sixteen light years of our sun.

The first list includes all the very bright stars that we know by name together with some bright southern ones that we are unable to see from northern latitudes. They show a wide range in color from blue Rigel and Spica, yellow Capella, orange Arcturus to red Betelgeuse and Antares.

For all these stars, values of the parallax or distance have been found, but for the more distant ones the values are uncertain, as the parallax will be of about the same size as the unavoidable errors of measurement.

Figure 26 shows how these brightest stars vary in spectral class and in absolute magnitude. All spectral classes are present, but eleven out of the twenty are the very hot *B* or *A* stars. All twenty are more luminous than the sun, with its absolute magnitude of +5. In fact Rigel shines probably as brightly as 21,000 suns, and seven others are more than 1000 times as bright as the sun.

There is also an enormous difference between the distances of the nearest of these stars, Alpha Centauri, and

Rigel, the most distant. Rigel is about 540 light years away, which is too far for the accurate measurement of a trigonometric parallax. Alpha Centauri is only four light years away. If we consider the volume of space that we have covered before we corralled Rigel we see that it is some $(540/4)^3$, or more than two million times larger than that

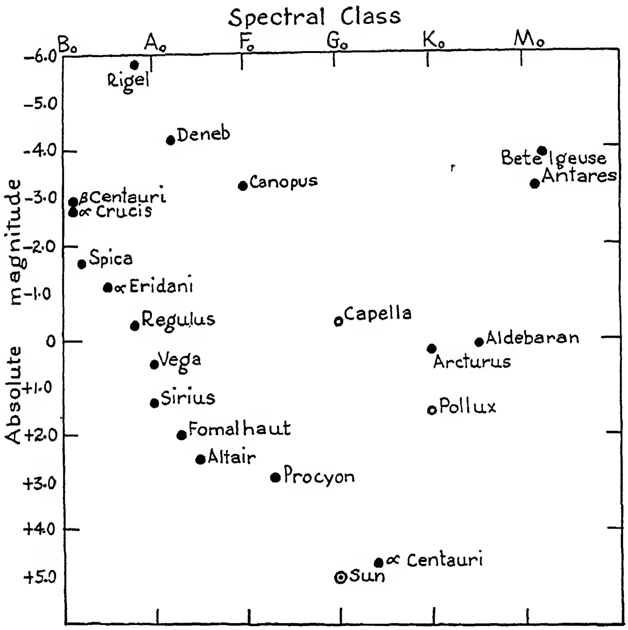

Fig. 26.—The twenty brightest stars.

which we would have to explore to find Alpha Centauri. This makes us suspect that such stars as Rigel, and to a lesser extent the other bright class *B* stars, must be very rare objects in space as compared with Alpha Centauri, which is the star most like our sun in spectrum and luminosity.

The two *M*-type stars, Betelgeuse and Antares, are among the very luminous stars. Since their surfaces are compara-

tively cool they must be very large to give off so much light. They are among the few stars whose diameters are large enough to be measured directly. The diameter of Antares

TABLE 1

THE TWENTY BRIGHTEST STARS

Name	*Visual magnitude*	*Spectrum*	*Absolute magnitude*	*Luminosity (sun = 1)*	*Distance (light years)*
1. Sirius.....	1.6[d]	*A*0	+1.3	30.	8.6
2. Canopus..	−0.9	*F*0	−3.2	1900.	100.
3. α Centauri	0.3[t]	*G*4	+4.7	1.3	4.28
4. Vega.....	0.1	*A*0	+0.5	63.	27.
5. Capella...	0.2[d]	*G*0	−0.4	150.	42.
6. Arcturus..	0.2	*K*0	+0.2	83.	33.
7. Rigel.....	0.3	*B*8 pec.	−5.8	21,000.	540.
8. Procyon...	0.5[d]	*F*3	+2.9	6.9	11.1
9. Achernar..	0.6	*B*5	−1.1	280.	70.
10. β Centauri.	0.9	*B*1	−2.9	1400.	190.
11. Altair.....	0.9	*A*5	+2.5	10.	15.7
12. Betelgeuse.	(0.9) Variable	*M*2	(−3.9)	3600.	300.
13. α Crucis..	1.4[d]	*B*1	−2.7	1200.	220.
14. Aldebaran.	1.1[d]	*K*5	+0.1	91.	53.
15. Pollux....	1.2	*K*0	+1.5	25.	29.
16. Spica.....	1.2	*B*2	−1.6	440.	120.
17. Antares...	1.2[d]	*M*1	−3.2	1900.	250.
18. Fomalhaut.	1.3	*A*3	+2.0	16.	23.
19. Deneb....	1.3	*A*2 pec.	−4.2	4800.	400.
20. Regulus...	1.3[d]	*B*8	−0.3	130.	67.

[d] = *double.*

[t] = *triple.*

is probably three Astronomical Units, that of Betelgeuse four. A star that is so big as to exceed the size of the orbits of the earth or even of Mars around the sun is a giant in every sense of the word!

TABLE 2

LIST OF STARS NEARER THAN SIXTEEN LIGHT YEARS

No.	*Name*	*Visual magnitude*	*Spectrum*	*Absolute magnitude*	*Luminosity*	*Distance (light years)*
1	Sun	−26.7	*G*0	+5.	1.	
2	α Centauri *A*	0.3	*G*4	4.7	1.3	4.28
3	α Centauri *B*	1.7	*K*1	6.1	.36	4.28
4	α Centauri *C*	11.	*M*	15.4	.000069	4.28
5	Barnard's star	9.7	*M*6	13.4	.00044	6.05
6	Wolf 359	13.5	*M*8	16.6	.000023	8.0
7	Lalande 21185	7.6	*M*2	10.6	.0058	8.4
8	Sirius *A*	−1.6	*A*0	1.3	30.	8.6
9	Sirius *B*	7.1	*A*5	10.0	.010	8.6
10	Ross 154	11.	*M*6	13.8	.00030	9.1
11	*L* 789-6	12.3	*M*?	14.9	.0001	9.8
12	Ross 248	12.	*M*6	14.5	.00016	10.5
13	ε Eridani	3.8	*K*0	6.2	.33	10.8
14	τ Ceti	3.6	*K*0	6.0	.40	10.9
15	Procyon *A*	0.5	*F*3	2.9	6.9	11.1
16	Procyon *B*	10.8	...	13.2	.00052	11.1
17	61 Cygni *A*	5.6	*K*5	7.9	.069	11.1
18	61 Cygni *B*	6.3	*K*6	8.6	.036	11.1
19	ε Indi	4.7	*K*5	7.0	.16	11.2
20	Σ 2398 *A*	8.9	*M*4	11.2	.0033	11.5
21	Σ 2398 *B*	9.7	*M*5	12.0	.0016	11.5
22	Groomb 34 *A*	8.1	*M*1	10.3	.0076	11.7
23	Groomb 34 *B*	10.9	*M*6	13.1	.00058	11.7
24	B.D. −12° 4523	9.7	*M*4	11.9	.0017	11.9
25	Lacaille 9352	7.4	*M*2	9.6	.014	12.0
26	Ross 614 *A*	11.	...	13.1	.00058	12.4
27	Ross 614 *B*	13.?	...	15.?	.0001?	12.4
28	Luyten's Star	10.1	*M*4	12.2	.0013	12.5
29	Lacaille 8760	6.6	*M*1	8.7	.033	12.5
30	Kruger 60 *A*	9.8	*M*4	11.8	.0019	12.7
31	Kruger 60 *B*	11.3	*M*6	13.3	.00048	12.7

TABLE 2 (*Continued*)

No.	*Name*	*Visual magnitude*	*Spectrum*	*Absolute magnitude*	*Luminosity*	*Distance (light years)*
32	Kapteyn's Star	8.8	*M*0	10.8	.0048	12.7
33	Groomb 1618	6.8	*K*6	8.8	.030	13.0
34	Van Maanen's star	12.3	*F*0	14.3	.00019	13.3
35	Ross 780	9.5	...	11.3	.0030	14.3
36	C.D. −46° 11540	9.4	...	11.2	.0033	14.5
37	AOe 17415-6	9.1	*M*4	10.8	.0048	14.7
38	Wolf 424 *A*	12.6	*M*8	14.2	.00021	15.2
39	Wolf 424 *B*	12.6		14.2	.00021	15.2
40	C.D. −44° 11909	10.0	...	11.6	.0023	15.4
41	B.D. +43° 4305	10.2	*M*5*e*	11.8	.0019	15.5
42	C.D. −37° 15492	8.3	*M*3	9.9	.011	15.5
43	C.D. −49° 13515	8.6	*Ma*	10.2	.0083	15.6
44	Altair	0.9	*A*5	2.5	10.	15.7
45	o² Eridani *A*	4.5	*G*5	6.1	.36	15.9
46	o² Eridani *B*	9.2	*B*9	10.8	.0048	15.9
47	o² Eridani *C*	10.7	*M*5*e*	12.3	.0012	15.9

Note added in proof: Professor van de Kamp suggests that the following star be added to the list of nearest stars: Ross 128; Mag. 11.1; Spectrum *M*5; Absolute mag. 13.4; Lum. 0.00044; Distance 11.2 l.y.

Let us next look at the list of nearby stars given in Table 2. We find here that the four brightest ones were also in Table 1: Sirius, Altair, Procyon and Alpha Centauri. They are conspicuous stars in our sky because they are nearby rather than because of their exceptional luminosity. The rest of the stars are much fainter both apparently and absolutely. Only six others are visible to the naked eye; eleven lie between magnitudes six and nine and can be seen with a small telescope; twenty are between the ninth and twelfth magnitudes, and five are even fainter than the twelfth magnitude.

Unlike our first list, our second list is probably not complete. To bring this fact out clearly, we have compared it with the list of nearby stars given by Eddington in his book "Stellar Movements and the Structure of the Universe" which was published in 1914. In Figure 27 all stars given by Eddington are marked with a circle, those which have been added later are marked with a point. Six other stars, all fainter than +12, could not be included on the figure because their spectra have not yet been determined.

We are sure that once you look at Figure 27 for a few minutes and see how all the recently added stars trail at the tail-end of the diagram, you will wonder how much longer and bushier the tail would be if it were all revealed. In that wondering you will find astronomers joining you. They too would like to know how many more near neighbors we have. We can be quite sure that we shall probably not find them in the upper part of the diagram. Enough is known about the bright stars to convince us that it is not probable that there will be more near neighbors among them. But there are many faint stars with large proper motions whose parallaxes have not been measured and the next few years will undoubtedly add to the number of faint neighbors.

It is not believed, however, that the number will be increased very greatly. From the average speed of the stars near our sun the average total density of matter in our region of space can be estimated. This result leads us to believe that our present estimate of the total star density will not be doubled.

There are some very real differences between the kinds of stars on our two lists. The first list contains almost entirely what are known as giants and super-giants. They are of all spectral classes through *B* to *M*. Our second list comprises the dwarfs, or as they are sometimes called, the "main

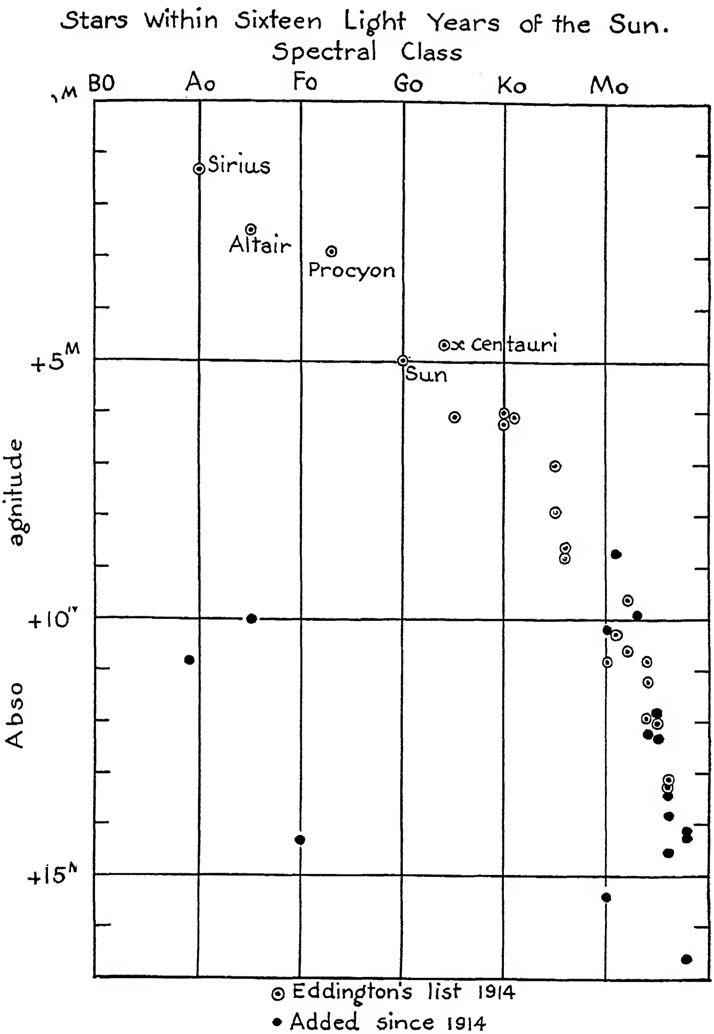

Fig. 27.—The nearest stars.

sequence" stars. We see in Figure 27 the very definite tendency for the stars to fall along a diagonal line—so that they become fainter as they become redder. We find no stars of class *K* or *M* which are of the same absolute magnitude as our sun; they are either brighter or fainter. Among our nearby stars we find none of the brilliant *B* stars or *G*, *K* or *M* giants. These show up among the bright naked eye stars because of their high intrinsic luminosity, but actually they are very rare objects in space, and those that we see are well beyond our sixteen light year sphere.

The most common variety of stars is the faint red *M* dwarf. They make up over half the list of our neighbors and when the unknown spectra of the faint ones are determined most of them will probably also be found to belong to this class. We say "probably" but not surely, for, as we see from our figure, there is still a chance that these faint stars may not be red dwarfs, but rather white dwarfs of class *A* or *F* of very low absolute luminosity.

There has been much written about the white dwarfs in the last few years and, while we know now a good deal about their nature, we hardly know how common they are in space. Certainly from Figure 27 we might seem justified in saying that they are at least as frequent in space as the bright *F* stars, or as the yellow stars like our sun, and much more numerous than the *B* stars or the red giants. The white dwarfs have been known for such a comparatively short time that the search for them is by no means complete. Two of those known are the faint companions of bright stars; one the companion to Sirius, the other the companion to o^2 Eridani.

We should bring out clearly at this time that our list of 47 nearby stars (including the sun) contains only 35 separate systems. Eight of these 35 stars are double, while two others are triple, thus bringing the total number of stellar bodies to

47. Since we are interested in finding how many varieties of stars there are, we have given each individual its place on the chart.

For the brightest stars we did not include their companions on the chart. Seven of the twenty brightest stars are double, one is triple. Duplicity is common among the stars.

The Distribution of Absolute Magnitudes

We can see from this comparison of the brightest stars and the nearest stars that we cannot satisfy our desire for completeness both in numbers and in kinds. In our small bit of space with its radius of sixteen light years we are fairly complete as to total numbers. But we are totally lacking the bright *B* stars and red giants that are so conspicuous among the brightest stars. If we go out far enough to include at least one of these, we have such a large volume of space that we are far from having complete information as to just how many other stars it contains.

Yet the astronomer wishes very intensely to know how many stars of given absolute magnitude and spectral class are present in a given volume of space. It lies within his power to count the stars to given limits of apparent magnitude. Such counts are a task which calls for ingenuity, skill, and patience. But by itself this is not sufficient. He does not wish to see the sky, as all primitive people see it, as a flat surface on which bright lights appear. It is not even enough that he has much more detail in his picture. What he must add is the third dimension so that he can see how the stars spread out in space. To do this he must know first what a typical sample of space contains. If he assumes that all space contains the same variety of star material in the same proportions, then, working with his apparent magnitudes, he can try to change his flat picture to a space picture.

The main objective of the present chapter is, therefore, to describe how we have succeeded in deriving the complete tabulation of the absolute magnitudes for a typical volume-sample in our Milky Way system. This tabulation, which lists the numbers of stars for successive intervals of absolute magnitude, is known among astronomers as the luminosity function. Figures 26 and 27 show at once some of the obstacles that we shall encounter in the derivation of the luminosity function. If we select our stars according to apparent brightness, we shall be woefully incomplete for the intrinsically faint stars, and if we turn first to the nearby stars we shall be exploring so small a volume of space that we find no supergiants at all in our first tabulation. It is clear that we shall have to attack the problem piece-meal. We shall first go after the bright end of our luminosity function, next after the faint end and then finally combine the two. Let us first explore further into space and see what we find if we go out far enough to include some of the rare stars of great intrinsic brightness.

The Bright End of the Luminosity Function

When we were speaking of the highest attainable accuracy in the measurement of trigonometric parallaxes, we wished that our earth moved in some larger orbit, such as that of Pluto, so that we would have a longer base line from which to make our measurements. How can we extend our base line? The earth shares the motion of our sun which is known to be moving with reference to the nearby stars at a rate of twenty kilometers per second in the direction of the constellation Hercules. Can this displacement of the earth be used to give us different positions from which to measure shifts of the stars' positions?

Before we try to answer that question, let us look in some detail at the methods by which the motion of the sun has

been studied. If we examine the available radial velocities for the brighter stars, what effect of the solar motion do we find?

Figure 28 shows a projection of the sky, so drawn that equal areas on the sphere are equal areas on the paper. It would be better if we could attach a little sphere to this book, but since that is impossible the projection will have to do. The sky has been divided into 94 equal areas. For each of these regions the available radial velocities of the naked

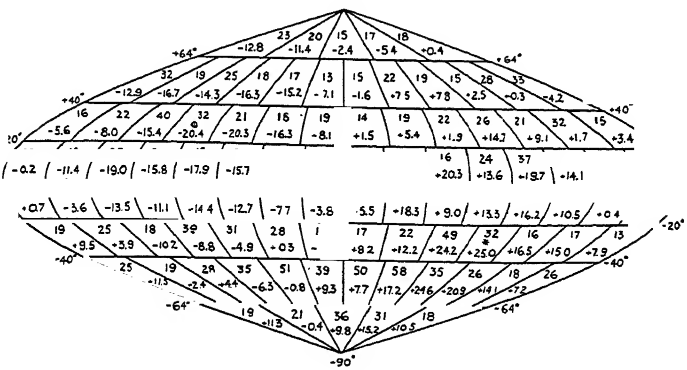

Fig. 28.—The sun's motion from radial velocities.

The distribution of the radial velocities of 2149 naked-eye stars. Lick Observatory.

eye stars have been averaged. Altogether the radial velocities of 2149 stars were used so that in each area there were on the average some twenty stars.

If the sun were at rest and the stars moving at random, there should be roughly as many positive as negative values for the radial velocities and the resultant average should be close to zero. Figure 28 shows what we actually find from the observations. The stars near the circle mark in upper left part of the figure have an average radial velocity of -20 kilometers per second; those near the asterisk in the lower

right hand part are of the order of +20 kilometers per second. Since the negative value indicates approach, it would seem that, as viewed from the sun, all the stars in one part of the sky are marching toward us; in the opposite region they are moving away.

Who is to blame, our sun or the stars? So long as we have no fixed landmark we cannot decide that question, but the simpler assumption, of course, is that the effect is due to the solar motion. With reference to the naked eye stars, the sun

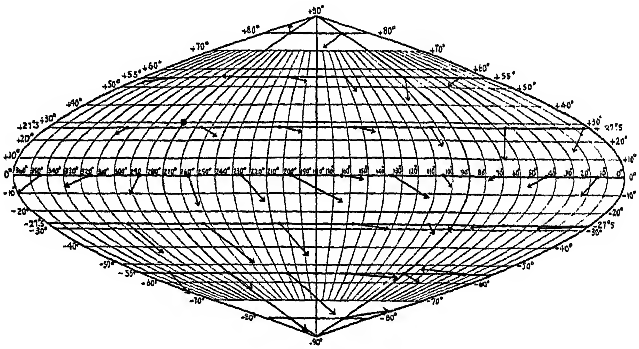

Fig. 29.—The sun's motion from proper motions.

The distribution of the proper motions of 726 A stars of the fifth magnitude.

is moving toward a point in the constellation of Hercules and not far from the bright star Vega at the rate of twenty kilometers per second. The circle mark in Figure 28 is called the *apex* of the sun's motion; the asterisk the *antapex*.

At the rate of twenty kilometers per second, in the course of a year of slightly over 31,500,000 seconds, the sun will travel 630,000,000 kilometers, or the equivalent of 4.2 Astronomical Units. Our earth moves therefore steadily along with the sun at the rate of 4.2 Astronomical Units per year. After an interval of twenty five years we are more than one hundred Astronomical Units from our starting place.

We can take sights of the stars as we march along and measure their average displacements.

Let us now see how the proper motions of the stars are effected by the sun's motion. Figure 29 is the same projection of the sphere that we had in Figure 28 but this time we have chosen to look into the proper motions of 726 *A* stars of the fifth apparent magnitude. They were divided into 42 groups according to their positions on the sky and for all groups we determined the average proper motions which are shown by the lengths of the arrows. These arrows are necessarily very much out of scale with the dimensions of our globe.

You will notice that most of the arrows seem to be pointing away from the solar apex and toward the solar antapex. With respect to the sun, the stars are moving toward one direction, or vice versa, our sun is moving in the opposite direction with respect to the *A* stars.

Since proper motions are angular displacements on the sky they will tend to be largest along the circle at right angles to the direction in which we are traveling, or, on the figure, along the projection of the circle that falls halfway between the apex and the antapex. The average of these maximum lengths is of the order of $0''.040$ per year for the *A* stars in Figure 29.

How can we combine that with the value that we found from the radial velocities of 20 kilometers per second or 4.2 Astronomical Units a year? We must remember here one outstanding difference between radial velocities and proper motions. Radial velocities do not depend at all on the distances of the stars. So long as the star is bright enough to appear on a spectrum plate its radial velocity can be determined in kilometers or miles per second and it matters not at all whether the star is nearby or very distant. Proper motion, on the other hand, varies with the distance, growing

smaller as the distance increases. The effect of the solar motion on the proper motions of the stars will therefore depend on the average distance of the group of stars under investigation. The effect will be larger for the nearby stars, just as for a train traveler the telegraph poles will appear to whiz backward while the distant mountains slowly recede.

You see now why we chose the proper motions of a group of *A* stars all of one apparent magnitude, whereas for the radial velocities we had a wide range of brightness. For the *A* stars there is not the division into giants and dwarfs that occurs in the later type stars so all the *A* stars of the fifth magnitude will be at about the same distance. What is that average distance?

By definition the parallax of a star is the angular displacement corresponding to one Astronomical Unit at the distance of the star. We have here an angular displacement of $0''.040$ per year which corresponds to 4.2 Astronomical Units at the average distance of the group of stars. The mean parallax for our *A* stars is therefore equal to $0''.040/4.2 = 0''.0095$ and their average distance is of the order of 105 parsecs or 340 light years.

This distance is beyond the distance for which reliable trigonometric parallaxes can be obtained. We shall have to remember that it is only an average distance and that it may be considerably in error for an individual *A* star. But it is a reliable average and we can now go one step further and compute from it the corresponding average absolute magnitude for our *A* stars. For a star of apparent magnitude 5.5 at a distance of 105 parsecs, the absolute magnitude can be computed from the formula:

$$M = m + 5 - 5 \log r$$

which in our special case gives

$$M = +0.4$$

as the mean absolute magnitude for our *A* stars.

Our method of measuring mean parallaxes can be applied to any group of stars with known proper motions, provided that these stars are evenly distributed over the sky. It is still applicable for groups of stars that have an average proper motion of 0″.008 and that may, therefore, be five times as far away as the *A* stars in our special example. If radial velocities happen to be available we can check up to see whether or not the solar motion is of the same type as that shown by the stars in Figure 28 and if all is well we can immediately compute a mean parallax, a mean distance, and a mean absolute magnitude.

Fig. 30.—P. J. van Rhijn of Groningen.

The method of mean parallaxes has one great advantage over the basic trigonometric method: the total displacement from which the mean parallax is found increases with time. By waiting longer we can obtain increasingly accurate values for the proper motions and so more reliable mean parallaxes. If the stars are so distant that we do not get a measurable effect in ten years we can wait twenty, forty, or, if necessary, a hundred years.

With our trigonometric parallaxes we cannot reach beyond distances of 200 to 300 light years, but with our mean parallaxes we can gather information that is still reasonably accurate for distances of 1500 light years and over.

Fortunately we do not have to depend exclusively on the evidence from mean parallaxes for the stars beyond reach of the trigonometric method. The method of spectroscopic parallaxes, which we have already described in the preceding chapter, is a powerful ally. From the differences in line

characteristics among the stars of a given spectral class we can not only distinguish between supergiants, giants and dwarfs, but also find out whether the star is a bit bright for a dwarf or just a shade below par.

By a combination of the results of the various methods we have, during the past twenty years, obtained reliable data on the distribution of the absolute magnitudes of the stars.

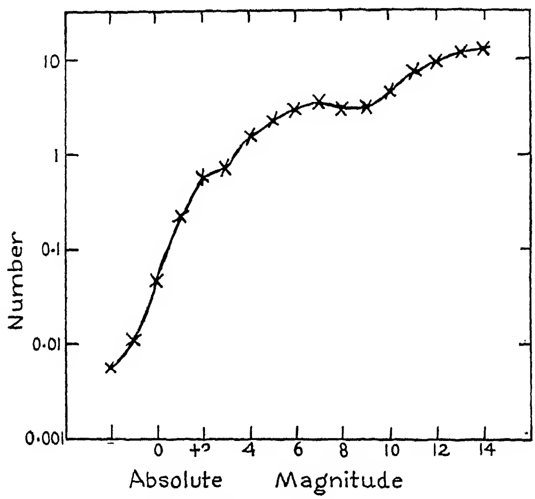

Fig. 31.—The luminosity curve.

The general luminosity function according to van Rhijn and Schwassmann.

The pioneer investigations of Kapteyn were followed by extensive studies by Seares and van Rhijn. The most dependable luminosity function that we have today is that of van Rhijn and Schwassmann, which has been reproduced in Figure 31. The diagram shows the distribution of the absolute magnitudes for the stars of all spectral types combined. It is probably reliable for the stars with absolute magnitudes between -2 and $+7$. The bright end can not

be much improved for the present, but if we return to our study of the sun's nearest neighbors we may be able to find out more about the faint end.

The Faint End of the Luminosity Function

How can we select the stars that will probably have measurable parallaxes from among their more distant brethern that appear to be equally faint? It would be a thankless task to measure the parallaxes of all the stars, say of the tenth or twelfth apparent magnitude, for we should probably find not one out of hundred that was measurable. The proper motions will help us to select the nearer stars. The linear speeds of the stars have a small range but there exists a tremendous range in the true luminosities. Linear speeds range from 5 to 50 kilometers per second for the majority of the stars. If we find a star with an annual proper motion of 1″ we can be reasonably sure that the parallax lies between 1″ and 0.1″. Even the lower limit brings the star close enough to make it a prize for the prospective measurer of its trigonometric parallax. If we wish to study the faint end of the luminosity function we naturally turn to proper motions. We choose two plates of the same region taken twenty to forty years apart, place them in a blink microscope as described in Chapter 2 and pick out the large proper motions. Wolf and Ross have made a fairly complete search for the northern sky and during the past ten years Luyten at Minnesota has about cleaned up the southern hemisphere. Parallax observers have put the promising objects on their observing lists and many parallaxes of nearby stars have been obtained. Van Maanen, working with the large reflector at Mount Wilson, has especially enriched our knowledge in this field. These stars of large proper motion are easy prey for those who wish to discover white dwarfs. A star with a large proper motion

that has an *A* type spectrum, or a small or zero color index, is almost certain to be a white dwarf. Most of the white dwarfs discovered by Kuiper in recent years were put on the suspected list because of their large proper motion.

The ultimate aim of all large proper motion surveys is the derivation of the luminosity function for stars that are intrinsically fainter than our own sun. Figure 32 gives the

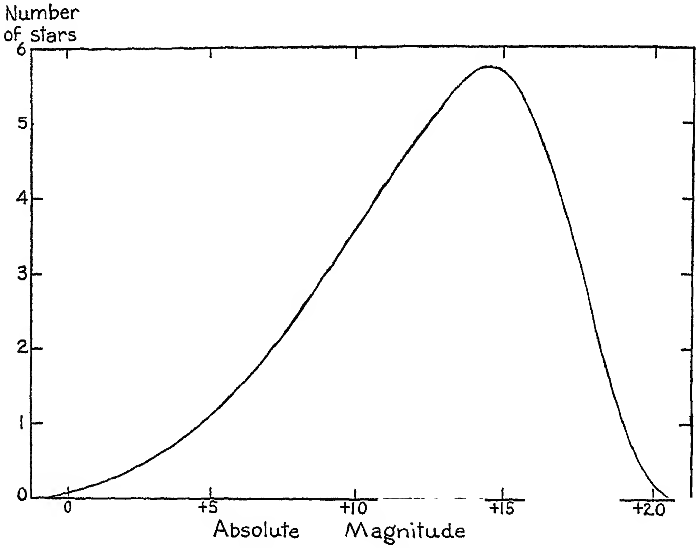

Fig. 32.—Luyten's luminosity curve.

The general luminosity function for the stars within sixteen light years of the sun, according to Luyten.

final result of Luyten's analysis. The curve shows that, as far as we can tell today, the stars of absolute magnitudes +14 or +15 (only one or two hundredths of one per cent as bright as our sun!) are by far the most numerous, if we take a complete census for a selected volume of our Milky Way system. The stars of absolute magnitudes −3 or −5 are apparently as rare as college presidents or state governors!

The Russell-Hertzsprung Diagram

So far we have put most emphasis on the general luminosity function which takes in all spectral classes together. We shall find many uses for the curves of Figure 31 and 32 in later chapters, but not infrequently shall we wish to know the average absolute magnitudes of giants and dwarfs of

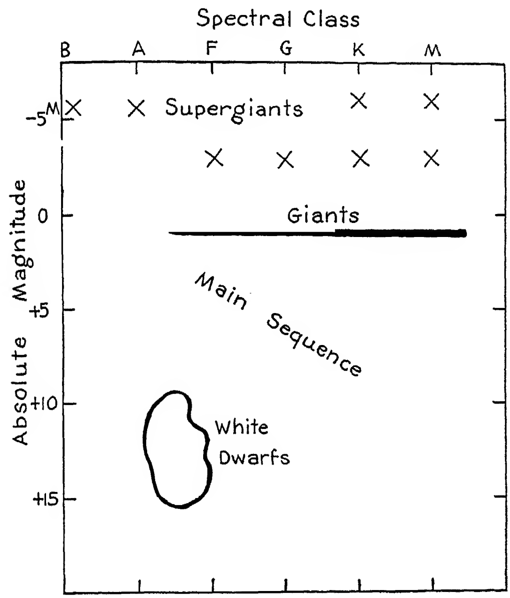

Fig. 33.—A schematic Russell-Hertzsprung diagram.

particular spectral classes. Figures 26 and 27 already tell some of the story, but for the sake of completeness we shall close this chapter with a famous diagram, which carries the names of two of the greatest astronomers of our times, the Russell-Hertzsprung diagram. Figure 33 shows the diagram with the main sequence and giant branches drawn in. The mean absolute magnitudes of the *A* to *M* main sequence and

giant branches have been taken from the investigation of van Rhijn and Schwassmann. The data on the very luminous *O* and *B* stars come from a recent compilation by Stebbins, Huffer and Whitford. The supergiants have been indicated by crosses; the white dwarfs are in the lower left part of the diagram.

Fig. 34.—H. N. Russell of Princeton.

Photograph by Harris and Ewing.

Fig. 35.—Ejnar Hertzsprung of Leiden.

The diagram indicates only the mean values of the absolute magnitudes of the stars in the main sequence and giant branches. The individual values for the absolute magnitude will generally be close to the mean. Some stars are found in the empty spaces in our diagram between the average values. Some of these cases will be due to unavoidable inaccuracies in the observational data, but all the stars do not conform rigidly to the rules set up by the majority.

4

REACHING OUT—THE SYSTEM TAKES SHAPE

Our Distant Neighbors

In the preceding chapter we made a census of the population in a fairly small sample of our galactic system, the region within two or three hundred light years of our sun. Armed with this information we can now set out to analyze the observations on stellar distribution for the more remote parts of our Milky Way. We wish to learn the size and extent of the whole galaxy, its shape, and the sun's position in the system.

It is natural that we should expect to solve this problem through analysis of complete data on stellar distribution. Unfortunately, what seems like a main thoroughfare turns out to be a dead-end road. We shall find that in spite of all our statistical information on the distribution of magnitudes, spectra, colors and motions, we cannot penetrate to the heart of our galaxy. We shall instead have to make use of variable stars, clusters, and distant highly luminous objects, such as novae and planetary nebulae. First let us, however, investigate the possibilities and the limitations of a wholesale attack through counts of all stars.

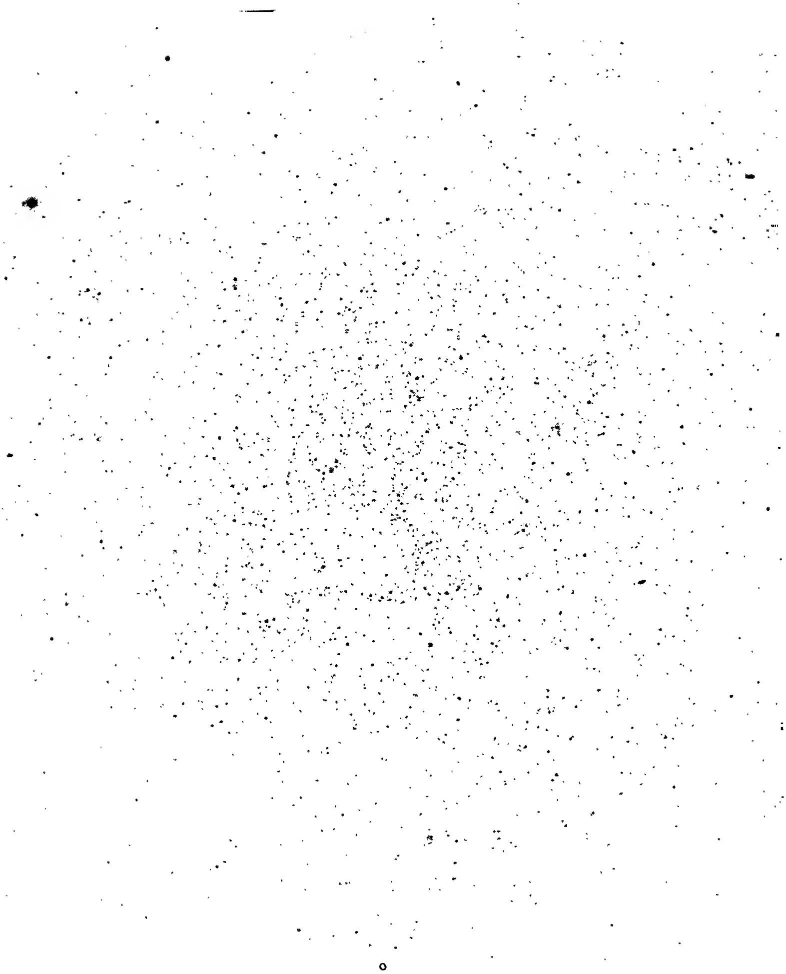

Fig. 36.—The Milky Way in Monoceros.
From a photograph taken by Ross with a 5-inch camera.

We can show most effectively what is involved by giving a specific example. Some parts of the Milky Way in Monoceros appear very smooth and regular. Miss Cannon at Harvard has classified the spectra of all stars to the eleventh magnitude for a Milky Way field directly north of the bright star Sirius. We can count, for example, the number of stars with spectral types *B*8 to *A*0 to successive limits of apparent magnitude for an area of one hundred square degrees. All stars counted in this area are contained in a cone with its vertex (that is the technical name for the place where the ice cream drips out!) at the sun and with an opening angle of eleven degrees.

The result of the count is that we find in that area 45 *B*8 to *A*0 stars brighter than the eighth magnitude, 96 between the eighth and ninth, 198 between the ninth and tenth, and finally 731 between the tenth and eleventh magnitudes. Now we know from our description of the Russell-Hertzsprung diagram that the *B*8 to *A*0 stars have mean absolute magnitudes close to 0.5. With the aid of our formula:

$$M = m + 5 - 5 \log r$$

we can find the average distances of the *A* stars for each value of the observed apparent magnitudes. The resulting distances in light years are:

Apparent magnitude = 8; distance = 1000 light years
Apparent magnitude = 9; distance = 1600 light years
Apparent magnitude = 10; distance = 2600 light years
Apparent magnitude = 11; distance = 4000 light years

As the distance increases our cone includes a progressively larger volume. The *A* stars brighter than eighth magnitude are spread over a total volume of ten million cubic light years, whereas the total volume for the stars brighter than the ninth, tenth and eleventh magnitude are respectively

forty, one hundred and sixty, and six hundred and forty million cubic light years.

We counted 45 *B*8 to *A*0 stars brighter than the eighth magnitude. If the numbers were to increase as the sizes of the volumes, the totals brighter than the ninth, tenth and eleventh magnitudes should have been 180, 720, and 2880. The observed totals 141, 339, and 1070 fall short of the predicted numbers.

The shortage of observed over predicted *A* stars means that either the *A* stars thin out rapidly as we move away from the sun, or, that the more distant *A* stars are partly dimmed by interstellar obscuration. Both causes are generally at work.

Our special example of the *A* stars is not unique. Wherever we turn along the belt of the Milky Way we find that the star numbers predicted on the assumption of constant star density and no interstellar absorption, are much larger than the observed star numbers. This holds for separate spectral classes as well as for general starcounts. The interpretation of observed total numbers is, therefore, not very simple. We shall see in later chapters that there are ways in which we can estimate the amounts of obscuration for a particular field, but these estimates are at best only rough approximations.

The interstellar absorption has really a double effect. First, it makes it difficult to compute accurate variations in the star density from counted totals. Second, the light of the stars in the galactic belt beyond ten thousand light years from the sun is obscured so much that most of these stars are beyond the reach of modern telescopic equipment. Moreover if we take ten thousand light years as the practical limit of exploration for starcounts and spectral surveys, we shall not learn much about the large scale properties of our galaxy.

We shall, therefore, have to search for other ways to find the general outlines of our galactic system. If statistical surveys do not work, can we perhaps hope to find some indication about the structure of the Milky Way system from the study of some special objects that come through on our photographs in spite of the interstellar fog? We naturally turn to the objects that we have already mentioned, to star clusters, galactic as well as globular, to variable stars, novae and planetary nebulae.

Galactic Clusters

On any clear night we notice, apart from the general hit-or-miss arrangement of the stars, a few places where the stars are closely clustered and seem to belong together. The Pleiades, or Seven Sisters, the Praesepe, or Beehive, cluster, the Hyades in Taurus, the double cluster h and χ Persei; these have all been known since antiquity. To these naked eye clusters telescope surveys have added many more groups.

The stars of galactic clusters are close together in space, not merely chance arrangements. If these clusters are real and of some lasting quality, all their stars should share a common motion. They should, therefore, move through space in parallel paths, and with identical speeds. If the group covers a large area of the sky—as for example, the Hyades—the arrows which represent the directions of motion of different stars in one cluster will all seem to pass through one point on the celestial sphere, just as railroad tracks seem to meet on the horizon. We generally refer to the galactic clusters that are close enough to us to show a measurable proper motion and a convergent point as moving clusters. The Hyades is the proto-type of a moving cluster.

Lewis Boss first detected the convergent motion for the Hyades when he was preparing his catalogue of proper

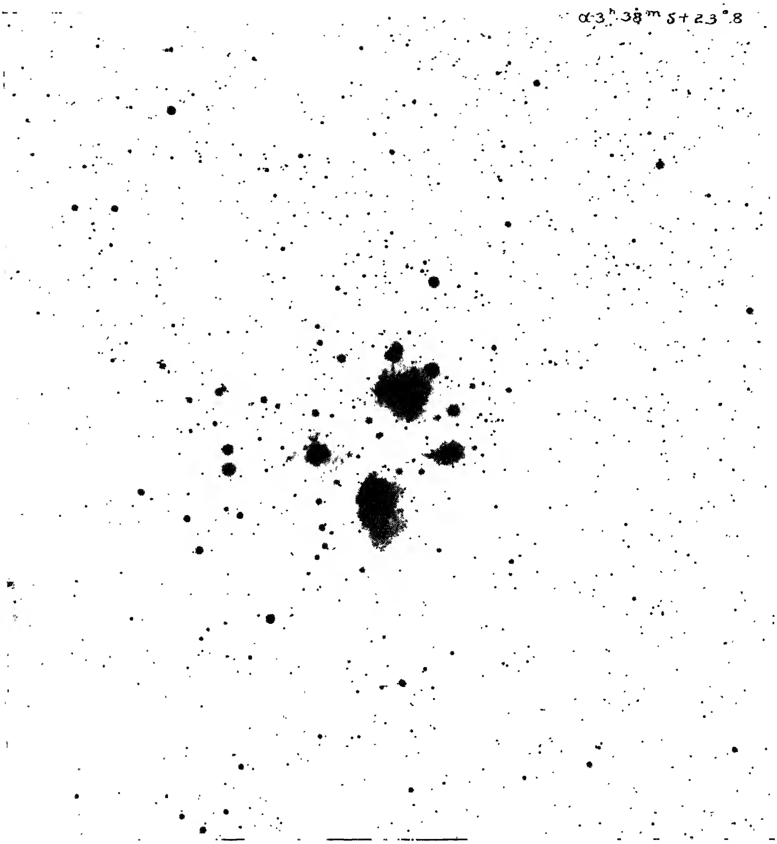

Fig. 37.—The Pleiades Cluster.

From a photograph by Barnard. The Pleiades are embedded in nebulosity.

motions. For this cluster the proper motion is large, and it is possible to sort out accurately the stars which belong to the cluster from among the field stars. Since the distance can be measured it is possible to build up a picture of the cluster, discover the kind of stars it contains, and find how closely

they are packed. The Hyades form a slightly elongated system.

The total number of moving clusters known is rather small, since most galactic clusters are so far away that they do not show measurable proper motion. But in spite of the

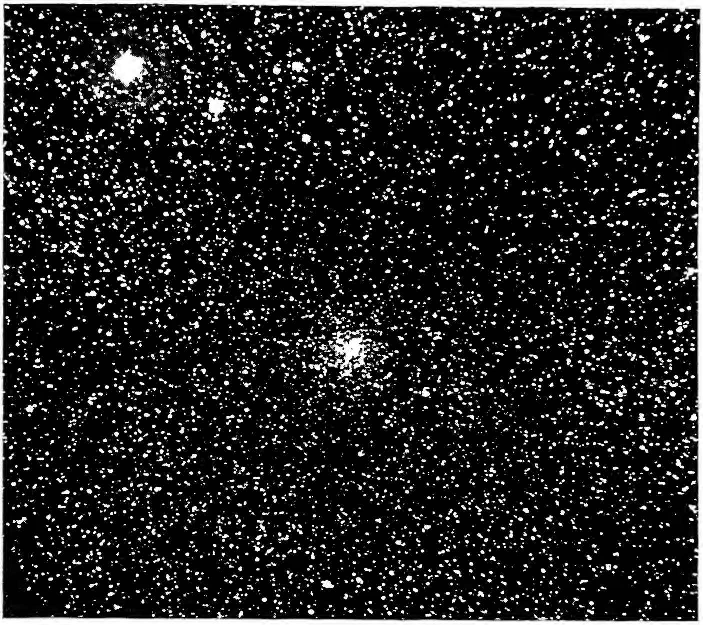

Fig. 38.—The Galactic Cluster N.G.C. 6838.

This photograph was taken by Cuffey at the Link Observatory in Indiana.

absence of observable motion we can learn much about the more distant galactic clusters. Some are rich in numbers of stars, others are little more than slight condensations against the background of the sky. After omitting the globular clusters we are left with some four hundred strictly galactic clusters. There are probably many more in our Milky Way

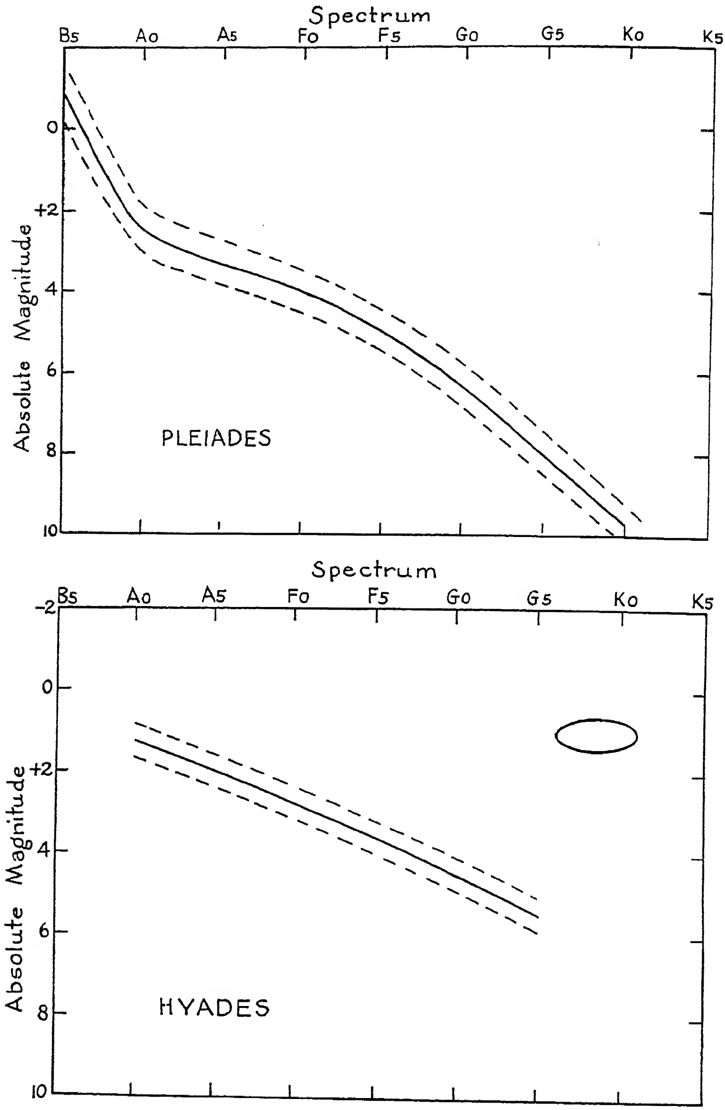

Fig. 39.—The Russell-Hertzsprung diagrams for the Pleiades and the Hyades.

system, but the more distant clusters are not noticed against the rich stellar background along the Milky Way. An early catalogue of clusters and nebulae was compiled by the French astronomer Messier. The New General Catalogue by Dreyer gives the positions of many fainter objects. Clusters are frequently identified by their Messier or N.G.C. number.

It is possible to classify the spectra of many of the stars in the nearer clusters. The observed spectral classes can be plotted against the computed absolute magnitudes. Figure 39 shows the diagrams for the Pleiades and Hyades clusters, which resemble incomplete Russell-Hertzsprung diagrams. In the Pleiades the red giants are lacking, while the blue giants are absent in the Hyades. It is, however, significant that the mean absolute magnitudes for the giants and dwarfs in clusters do not differ appreciably from those for the stars of the same spectral class in the vicinity of the sun. We can use this important uniformity to measure distances. For example, suppose we have a cluster whose distance cannot be found by direct means, but in which spectral classes can be determined for a good fraction of the membership. We can estimate the approximate distance by fitting a diagram which gives apparent magnitude and spectral class in the cluster on to the standard Russell-Hertzsprung diagram. If we find, for example, a mean apparent magnitude 10.5 for the *A* stars in a cluster, we can read the corresponding mean absolute magnitude +0.5 from our standard Russell-Hertzsprung diagram. In the absence of absorption, the distance of this cluster can be found from the formula

$$5 \log r = m - M + 5,$$

which in our case would give a distance of one thousand parsecs, or 3260 light years. Trumpler at Lick has deter-

mined the distances for many galactic clusters in this fashion.

The clusters beyond the reach of spectral classification present a difficult problem. Trumpler found that for the clusters with measured distances there was little spread in the true diameters, if the clusters were grouped according to the total number of stars and degree of concentration of stars toward the center. He then classified all known clusters according to total membership and degree of central condensation, and computed the distance by comparing the observed angular diameter with the true average diameter for the group.

Fig. 40.—Robert J. Trumpler of Lick Observatory.
Photograph by Coleman.

For some of Trumpler's clusters two estimates of distance were now available; one from the spectral-magnitude array, the other from the apparent diameters. When the values were compared, agreement was generally found for the nearby clusters, but for the distant clusters the estimated distances from the observed diameters were smaller than the distances found from the spectral data which involved also the use of apparent magnitudes.

Attempts to explain the discrepancies as due to systematic errors of some sort failed. What could be the cause of the trouble? Trumpler was finally forced to conclude that the light of the distant clusters was dimmed by interstellar absorption. Such an absorption would not affect the distances found from the measured angular diameters. It

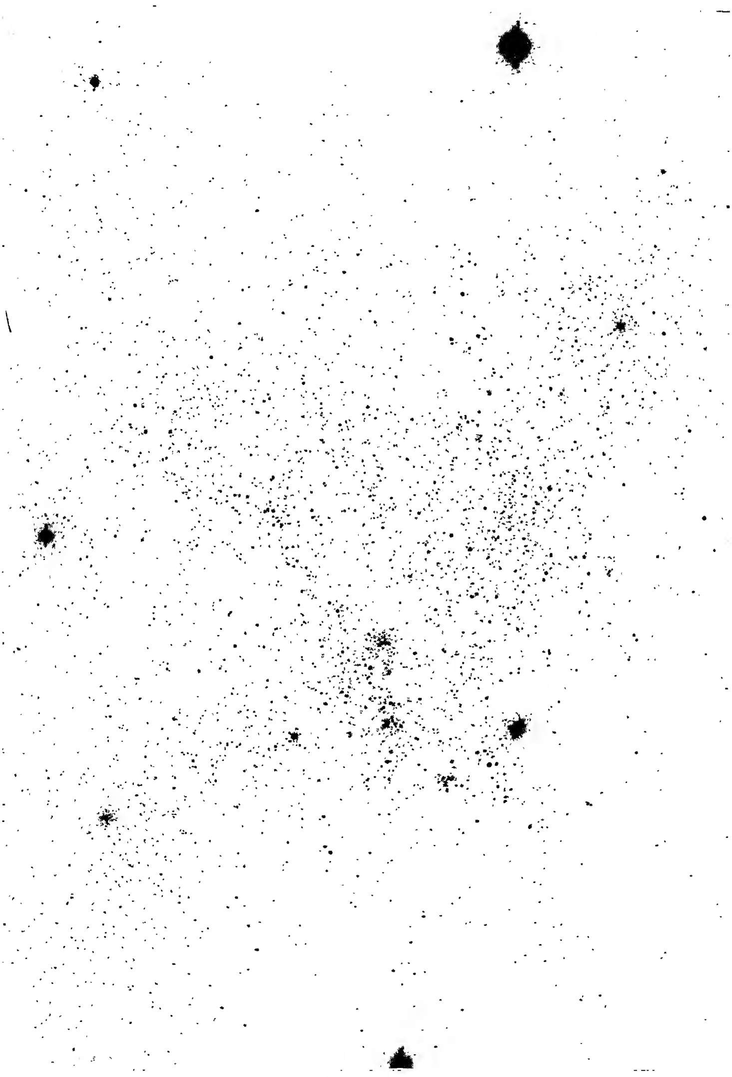

Fig 41.—The Milky Way in Auriga.

From a plate taken by Tabor at the Cook Observatory. This section of the Milky Way is noted for an abundance of galactic clusters.

would, however, affect the distances from the spectrum—magnitude arrays, for all apparent magnitudes would be measured too faint.

Trumpler's investigation of 1930 gave one of the first definite proofs for the presence of interstellar scattering of light. We shall have occasion to return again and again to the problems of interstellar absorption, but we note here that such an absorption may make it impossible to see very far in some directions in the Milky Way.

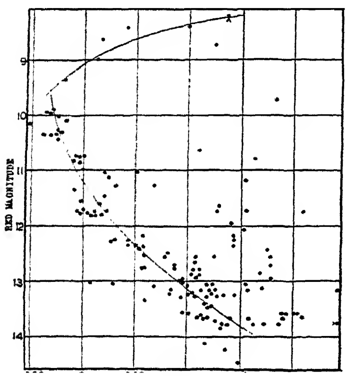

Fig. 42.—A typical color-magnitude diagram.

Measurements of colors and magnitudes by Cuffey have yielded this diagram for the galactic cluster N.G.C. 2281.

In recent years Cuffey has made extensive use of a method in which the colors of faint cluster stars figure prominently. While it is difficult to obtain spectra beyond the twelfth magnitude, stellar colors can be measured down to the sixteenth magnitude. One of Cuffey's color-magnitude arrays is reproduced in Figure 42. The main sequence is easily recognizable, and, by superimposing the color-magnitude array for stars in the vicinity of the sun upon the observed diagram, Cuffey has been able to estimate the total coloring (and, as we shall see later, also the total absorption) and the distance of each cluster.

The name galactic cluster indicates that these objects occur most frequently along the broad band of the Milky Way. The clusters beyond twelve to fifteen thousand light years are wholly unobservable. The fairly regular distribution of the known galactic clusters for the observed section

shows that our Milky Way system extends at least to those distances. The absence of observed galactic clusters at distances of twenty to thirty thousand light years does not tell us anything about the properties of the more remote parts of our galaxy, but serves only to remind us of the limits to which we can now penetrate by means of studies of galactic clusters.

We should now turn our attention to the globular clusters, but before doing so we ought to make the acquaintance of the widely distributed Cepheid and cluster type variables. It is by means of these variable stars that we find ways of employing the globular clusters in our attempts to reach the farthest parts of our galactic system.

Cepheid Variables

Every navigator learns to know the lights along a familiar coast. He knows the time intervals according to which they flash on and off, and after identifying them he can chart his distance from the shore and plan his course. The Milky Way provides such signal lights for the celestial nagivator. These are the Cepheid variables which repeat exactly and unendingly a characteristic pattern of increasing brightness followed by a slower decline. The periods, or times in which they repeat their patterns, are not the same for all the stars but again there is a law underlying the diversity. Once found, it became a powerful guide enabling the astronomer to steer his course to distances greater than those to which he could ever have ventured without its guiding light.

We are too apt to believe that the day of the explorer is over, and we wish, perhaps, that we lived in the age of Columbus, Sir Francis Drake, or Magellan. Yet probably most people of those days did not realize, or realized only vaguely, the changes that were taking place in man's

thoughts about the world. So today, how many people realize that in the past twenty-five years our knowledge of the universe has expanded far beyond what we would once have thought possible?

Sometimes science seems to advance through a slow step-by-step process, and then again, before we realize that we are ready for it, there is a sudden sweep forward. Such a sweep ahead was the work of Shapley on the distances of the globular clusters and the size of the universe. In that work the Cepheid variables played a major part.

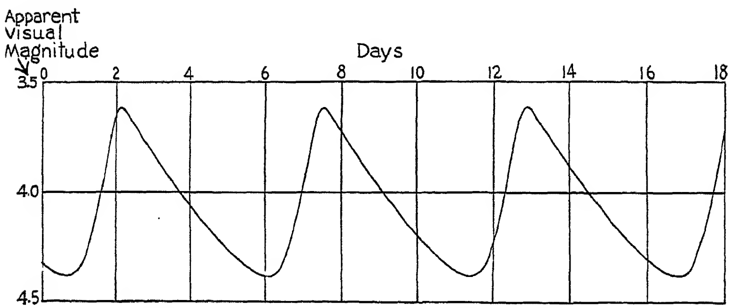

Fig. 43.—The light curve of Delta Cephei.

The diagram illustrates the changes in magnitude of the typical Cepheid variable.

The Cepheid variables are so named after the brightest one of their class, the star Delta of the constellation of Cepheus. It is an easily identified star, and if it is closely observed for a week or two, it is seen to change its brightness between the third and fourth magnitude, within an interval of five days. Figure 43 shows the light curve, where the time is plotted along the horizontal scale, and the magnitude along the vertical. We see that Delta Cephei rises quickly to its greatest brilliance, fading away more slowly. Over and over again unvaryingly it repeats this pattern of changing brightness.

Together with the change in brightness occurs a change in color, so that the star becomes redder as it grows fainter. With the aid of the spectroscope the radial velocity or motion in the line of sight is found to vary in the same period as the change of brightness. The time of greatest velocity of approach comes at or near the time of maximum light, the greatest velocity of recession comes at or near the time of minimum light. The most satisfactory explanation of these phenomena is that put forward by Shapley and Eddington, that the stars are slowly pulsating; now expanding, then contracting.

Most of the so-called Cepheid variables have periods of nearly a week. There are however fainter stars in the sky which also wink on and off but in a shorter period of time. Many have periods of about half a day. The short period Cepheids are frequently called "cluster variables," because Bailey, at Harvard, found that they were present in many globular clusters. Later, also at the Harvard Observatory, Miss Leavitt studied these variable stars in the Small Magellanic Cloud; that irregular mass of stars that almost seems like a bit of the Milky Way broken loose. She found a very important relationship between the periods of light variation and the average brightnesses of the stars. She noted as a curious fact that the longer the period of variation, the brighter the star appeared.

Fig. 44.—Solon I. Bailey of Harvard.

Photograph by Marshall.

Hertzsprung and later Shapley recognized this law as being an intrinsic quality of the stars. Since the Magellanic Clouds are aggregations of very faint stars they must be very far away. In that case all the stars can be assumed for practical purposes to be equally distant and the relation between the period of light variation and the apparent magnitudes will really be one between period and absolute

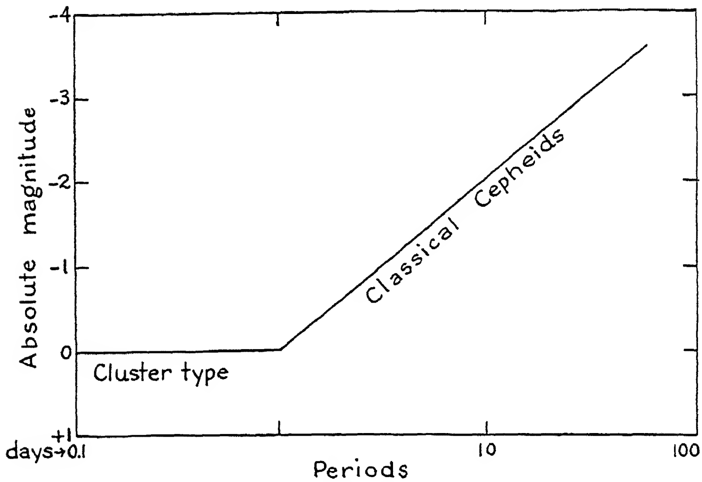

Fig. 45.—The period-luminosity relation.

A schematic diagram to illustrate how the average absolute magnitudes of cluster and Cepheid Variables are related to the periods of the light variation.

magnitude. The difficulty is to find the constant, or modulus, which must be subtracted from all the apparent magnitudes in order to change them to absolute magnitudes.

If we only knew the absolute magnitude of a single Cepheid of known period, we could use it to determine the "zero-point" of the period luminosity curve, and then the curve might be used to give the absolute luminosity of any Cepheid whose period has been observed. The nearest

galactic Cepheids are too distant for accurate measurement of their trigonometric parallaxes. It is necessary to determine the average parallaxes from the proper motions by the method of mean parallaxes described in Chapter 3. But the motions of the stars are small and their distribution over the sky is not uniform. Both factors introduce uncertainties in the parallax determinations, but it is clear that even the brightest Cepheids are very distant and highly luminous.

If the regular Cepheid variables near the sun prove too far away for accurate measurement of their absolute magnitudes, we should see if the nearest cluster variables are perhaps more cooperative. After Bailey's discovery of cluster variables in globular clusters, many of these variables were also found outside clusters. The apparent magnitudes of the brightest known cluster variables are more than three magnitudes fainter than those of the brighter Cepheids, but this is not necessarily indicative of greater distance, since the period-luminosity curve shows that the absolute magnitude of a typical cluster variable is well below that of the regular Cepheids.

The cluster variables have unusually high linear speeds and this renders them especially suited for studies of mean parallaxes. The average radial velocity of a Cepheid variable will generally not exceed 20 kilometers per second, but for the cluster variables velocities of the order of 100 kilometers per second are by no means uncommon. The high linear velocities lead to average proper motions for the cluster variables of the tenth magnitude and brighter that are far larger than those of the regular Cepheids. The larger size of the proper motions then makes possible the accurate determination of the mean parallaxes for cluster variables. From the mean parallaxes and the mean apparent magnitudes the zero point of the period-luminosity curve can be determined within a few tenths of a magnitude. We can

look forward to an accurate calibration of the period-luminosity curve from the results of an extensive current investigation by R. E. Wilson at Mount Wilson Observatory.

The period-luminosity relation is one of the most powerful tools of astronomical research. If anywhere in our galaxy, or in any other galaxy for that matter, we find a Cepheid or cluster variable, we can readily determine the distance of this variable. We determine the apparent magnitude and the period of light variation of the star. The period-luminosity relation tells us directly its absolute magnitude, and, without further effort, we find the distance r from the equation

$$\log r = m - M + 5$$

We have had to neglect interstellar absorption in the argument as presented so far. In many cases its effect is negligible and if this is not the case, we can try to take it into account.

The period-luminosity relation will find a place in almost every book of our series. It provides the needed measuring rod that allows us to penetrate to the remotest parts of our galactic system. We are reaching out ever farther from our sun. Cepheids and cluster variables in star clouds along the Milky Way and in the distant globular clusters have been patiently flashing on and off for centuries upon centuries and now finally the great day has come when we have learned to read their messages!

Globular Clusters

The total membership of typical galactic clusters ranges from twenty to at most a few thousand. The one hundred known globular clusters are in a class by themselves for they average at least one hundred thousand stars.

Until Shapley's classical investigations of 1916–1919 no measures of the distances of globular clusters were available. His studies of the cluster variables, discovered by Bailey and others, led to the first accurate distance estimates for these far-away objects. Bailey at Harvard had found periods and

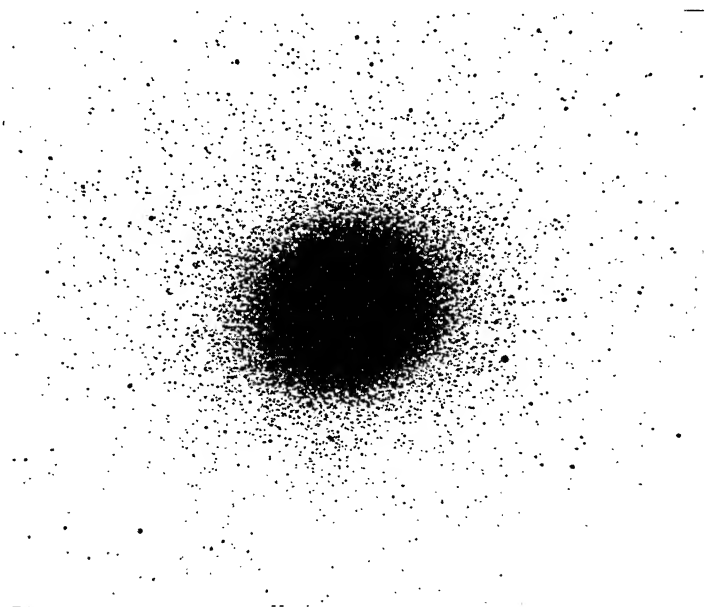

Fig. 46.—The globular cluster Omega Centauri.

From a photograph by John S. Paraskevopoulos taken with the 60-inch reflector at the Boyden Station of the Harvard Observatory.

light curves for variables in three globular clusters. With the aid of the sixty- and one hundred-inch reflectors at Mount Wilson, Shapley photographed great numbers of the cluster variables frequently enough to obtain accurate light curves, and consequently the distances of all globular clusters with known cluster variables could be found.

The variable star research yielded the distances for seven globular clusters. The data for these systems led then to the discovery of other criteria for distance. Shapley found that the absolute magnitude of the twenty-fifth brightest star was very nearly the same from one cluster to the next. For the clusters without variable stars reliable values for the distances could be obtained by assuming that the twenty-fifth brightest star had a mean absolute magnitude equal to −1.5.

Fig. 47: Harlow Shapley of Harvard.

Photograph by Bachrach.

Shapley found further that the cluster diameters in light years did not vary much among the clusters with well-determined distances. A second estimate of the distances of the clusters without known variable stars was then obtained by assuming their linear diameters to be equal to the average for the better known clusters.

By a combination of the various estimates Shapley was able to make a model of the system of the globular clusters and study its relation to the Milky Way. The most startling fact that emerged from Shapley's work was that the globular clusters, which clearly belong to our Milky Way, reach to distances far beyond any that had ever been considered before. The nearest globular cluster is almost as distant as the most remote galactic cluster!

Before the work of Shapley it had generally been agreed that our sun was not far from the center of the Milky Way system; that the stars thinned out in all directions away

from the sun; and that the diameter of the whole system would hardly exceed thirty thousand light years. Even after we apply rough corrections for interstellar absorption —which were not known in the days of Shapley's work on

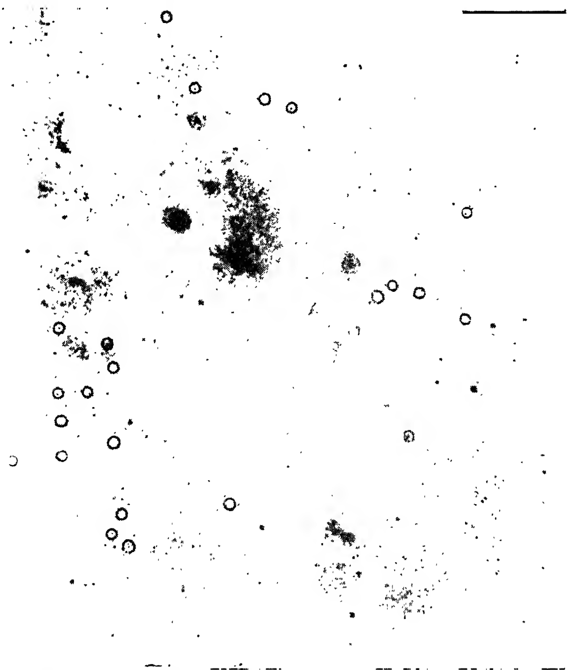

Fig. 48.—The globular clusters in Sagittarius.
The circles mark the position of the faint globular clusters.

globular clusters—the system of the clusters is found to measure at least one hundred thousand light years across.

Our sun is nowhere near the center of the system of the globular clusters. The eccentric position of our sun is indicated if we note, first, that all but very few of the known globular clusters are in one half of the sky, and secondly, that one third of all known globular clusters are found in a

region in Sagittarius that covers only two per cent of the whole sky. The center of the system of the globular clusters lies at a distance of thirty thousand light years from our sun in the direction of the star clouds in Sagittarius.

We are here primarily interested in the Milky Way system. What evidence is there bearing upon the relation between our galactic system and the system of the globular clusters? Do both systems have the same center and are their dimensions comparable? We have already given you the answers to these questions at the end of the first chapter, but this is the occasion to enter into more details.

The Galactic Center

The researches on globular clusters place the galactic center near a position marked as right ascension 17.5 hours, declination $-30°$. The crowding of the globular clusters toward this part of the sky is most spectacular; but if we examine other types of objects we find that the most distant among them share this preference for the Sagittarius region.

We might consider first the general appearance of the Milky Way in this part of the sky. The region of the Sagittarius Cloud is the brightest in the sky; its only rival is the Carina region in the southern hemisphere. Long-exposure photographs of the Milky Way show that the faint stars are more crowded together in the Sagittarius region than in any other part of the Milky Way, including Carina. From star-counts alone we would therefore select the Sagittarius region as the direction in which the faint stars are most concentrated.

Cepheid variables appear in great abundance in the Sagittarius region. Researches at Harvard by Shapley and his associates, especially Miss Swope, show that the most luminous Cepheids prefer the direction of Sagittarius and that they definitely support the hypothesis of a massive

center at a distance of thirty thousand light years from the sun.

Distant highly luminous objects such as novae, or new stars, and planetary nebulae show also a distinct preference for the region of Sagittarius. In brief, all data on stellar distribution point to the eccentric position of our sun in the galactic system.

So far, we have confined our discussion largely to the purely structural aspects of the Milky Way problem. We

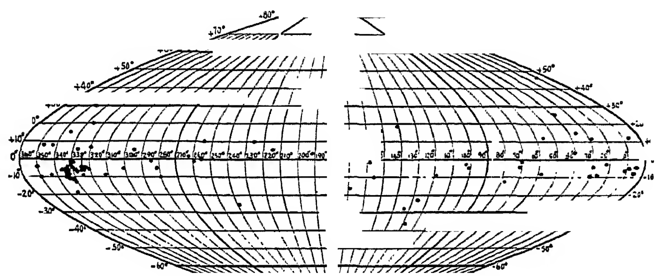

Fig. 49.—The galactic distribution of Novae.

The concentration of novae in the direction of the galactic center (longitude 325°) is pronounced. Data from Gaposchkin: Variable Stars.

wished to reach the remotest parts of our galactic system, but now that we are there, we begin to wonder what it all means. If there exists a distant, and presumably quite massive, center of our galaxy, can we then not trace the effects of its attraction in the motions of the stars? This problem is the subject of the next chapter, where we shall first describe the observed regularities in stellar motions and then show that the phenomena of star streaming, asymmetry in stellar motions, and galactic rotation are further corroborative evidence for the existence of a distant massive nucleus of our galaxy.

5

THE WHIRLING GALAXY

SO FAR WE HAVE ONLY CONSIDERED THE PURELY STRUCtural aspects of the problems of the Milky Way. What are the general outlines of the system? Where is the sun located with respect to the galactic center? In answering these questions we have called on data on the motions of the stars for the measurement of average distances of groups of stars, but we have now to consider what information on the Milky Way system can be derived from the observed regularities—and also lack of regularities—that are found in the proper motions and radial velocities of the stars.

We shall approach the problem of stellar motions in much the same way as the study of the structure of the galactic system. That is, we shall begin with the stars within a few hundred light years of our sun and then gradually reach out to explore the motions of the more remote stars and clusters.

NEAR THE SUN

In order to be quite specific, let us suppose that we hew from our Milky Way system a cube, measuring five hundred light years on each side, at the center of which is our sun. We begin our study by finding the motion of the sun with

respect to the average—the center of gravity would do—of all stars in the cube. We have shown in Chapter 3 how that can be done if we know the proper motions and radial velocities for a sufficient number of the stars. We found the

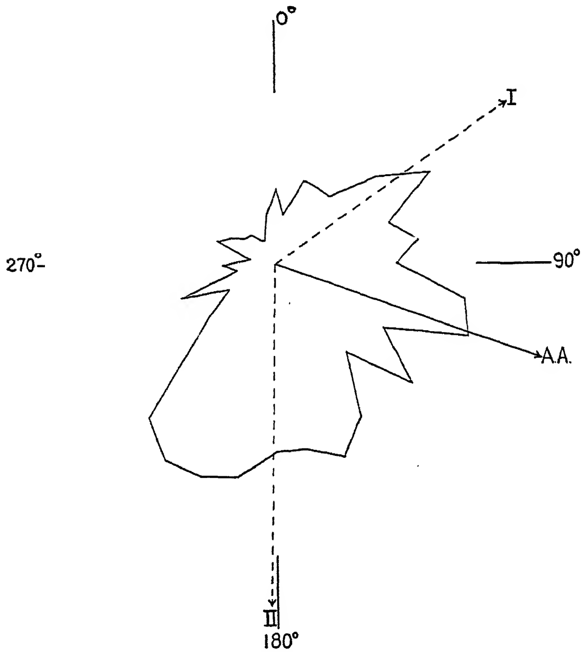

Fig. 50.—A typical star streaming diagram.

The diagram illustrates the distribution of directions of proper motions, measured by Smart, for a small region of the sky; the arrow "AA" marks the direction toward the Antapex.

sun to be moving at a rate of twenty kilometers per second toward a point in the constellation Hercules.

The discovery of the sun's motion toward the apex in Hercules does not really tell anything about the properties of the Milky Way system. Our sun is a star, like millions of other stars. Most stars move with velocities of the order of

ten to thirty kilometers per second with respect to the average of their neighbors and there is no reason why the sun should be different.

Throughout the nineteenth century astronomers were blissfully unaware of any regularities in stellar motions beyond those arising from the reflex of the sun's motion. Then, in 1904, Kapteyn of Holland announced the discovery of the two star streams. With this discovery came for the first time the realization that the stars are not moving in a perfectly haphazard fashion, but that their motions are subject to certain general laws.

Kapteyn's research dealt with the proper motions of the brighter stars in the sky. The celestial sphere was marked off into a number of sections—just as we did in Chapter 3 for the study of the solar motion—and in each of those sections Kapteyn counted the number of stars moving within certain narrow limits of direction. A plot of the proper motion arrows on a chart or on a celestial sphere will show directly how many are moving within fifteen degrees of the direction of the North Pole in the sky, how many within fifteen degrees of the north-west direction, etc.

A diagram, such as Figure 50, summarizes the observed distribution of directions in a convenient fashion. We draw for each particular direction an arrow, the length of which is proportional to the number of stars found travelling in that direction. By connecting the ends of these arrows by a line we obtain a clear representation for the distribution of the directions of proper motions for each section of the sky.

If the stars were moving perfectly at random, and if the sun had no motion of its own, the line connecting the points in the diagram would be almost circular. The sun's motion would have the effect of drawing this circle out into an elongated figure, resembling an ellipse, the long axis of which should point away from the apex of the sun's motion.

For fields not far from the apex and antapex the figure should be almost circular and the highest flattening should be found along the great circle on the sphere halfway between the apex and antapex.

To make a long story short, we find nothing of the kind. The curves near the apex and antapex are by no means circular, and simple figures shaped like ellipses are not observed. The characteristic feature is that the figures are bi-lobed. Generally two directions are found which the stars in a given section seem to prefer.

It was soon found that these streaming effects were not purely local. For each section we can draw the two preferred directions and if we plot these on a celestial sphere they appear to point pretty well to two points on the sphere. The points were called by Kapteyn the apparent vertices of his two star streams. If the observed streaming tendencies were of a random character, we would have found no regularity in the distribution of these arrows over the sphere. The fact that each stream shows a well-marked convergent point is excellent proof that the stars all over the sky show in their motions preferences for either Stream I or Stream II.

The Kapteyn star streaming bears some resemblance to the convergent effect observed for the stars of a moving cluster such as the Hyades cluster. In the case of the moving cluster the proper motions of all individual members were found to pass exactly through the convergent. The motions of the stars that belong to one of Kapteyn's streams show only a tendency to move along with the general stream motion rather than at right angles to it. They still insist on preserving their right to deviate considerably from the path of streaming instead of submitting to the Hyades-like regimentation.

As observed from the sun the two star streams move at oblique angles. It is not difficult, however, to correct for the

effect of the sun's motion and derive the position of the vertices as viewed from a star supposed to be at rest with respect to the average of all its neighbors. Kapteyn showed that the true vertices of star streaming, found after correcting for solar motion, fell at opposite points in the sky, one in Scutum, the other in Orion.

Fig. 51.—Karl Schwarzschild of Göttingen.

Fig. 52.—Sir Arthur Stanley Eddington of Cambridge.
Photograph by Lafayette, Ltd.

It was not surprising that the true vertices are diametrically opposite, because, by correcting for local solar motion, we have automatically balanced the motions in the streams. But it was surprising, and highly significant, that the line of the true vertices fell exactly in the Milky Way and we note in passing that it lies not far from the direction of the galactic center. An explanation was not directly forthcoming, but at the time of Kapteyn's discovery it was realized that this represented some major clue for the ultimate solution of the riddle of the Milky Way.

Subsequent researches by Eddington and Karl Schwarzschild and recent work by Smart, Knox-Shaw, Charlier, Oort and many others have confirmed and extended Kapteyn's work. Schwarzschild showed that it was not strictly necessary to assume the existence of two definite streams. The line of the two vertices marks a general direction of preferential motion. On the whole the stars seem to move rather along that line than at right angles to it. Originally the unequal number of stars in Streams I and II seemed to favor Kapteyn's hypothesis, but the recent work on the motions of telescopic stars has shown that this inequality disappears as we turn to fainter stars. At present, Schwarzschild's and Kapteyn's descriptions are considered equivalent.

Fig. 53.—W. M. Smart of Glasgow.
Photograph by Lafayette, Ltd.

Traffic in New York City provides a rough analogy with celestial star streaming. Most cars and busses move along the north-south avenues and traffic along the east-west streets is both slower and less dense. If we go one step further we find slower traffic at right angles to either direction, up and down the elevators. Fifth Avenue marks New York City's line of the true vertices!

The description of star streaming does not complete our survey of the observed regularities in stellar motions in the mythical cube that we introduced earlier in this chapter. We have to add cluster motion, the K-effect, and the asymmetry in stellar motions if we wish to be complete.

In Chapter 4 we made the acquaintance of moving clusters such as the Hyades and Pleiades. If we study the motions of the nearby stars we find evidence for some stars that are really very far apart and yet move in exactly parallel paths. Five of the seven stars in the Big Dipper form the very tenuous nucleus of the Ursa Major cluster. According to Smart of Glasgow, who has made a very careful study of this cluster, there are in all forty-two recognized members of this extended moving cluster; Sirius, in another part of the sky, is certainly its most conspicuous member.

For many years it was generally conceded that most brighter *B* stars were members of extended moving clusters, but Smart's researches have shown that the reality of these clusters is very doubtful. The *B* stars have very small motions of their own and the apparent moving cluster motions are in reality only the effect of the reflection of the sun's motion.

The so-called *K*-effect is very puzzling. If we take the means of radial velocities for opposite regions of the sky, the solar motion should average out and the means should all be zero. Because of fluctuations some of these averages might have small negative or positive values, but there is no reason why they should all come out positive. That, however, is exactly what happens if we consider the nearer *O* and *B* stars. The *K*-effect has been known for many years and a number of explanations, none of which is quite satisfactory, has been offered.

The slight red-shift for massive stars predicted by Einstein's theory of relativity may explain part of the effect, but does not account for all of it. Stream motion among the southern *B* stars is not supported by Smart's studies of extended moving clusters. A small part of the *K*-effect can be explained by the rotation of our galaxy and the patchy

distribution of the *B* stars but we are still without a satisfactory explanation of the *K*-effect.

We mention last of all the asymmetry in stellar motions. Even among the nearer stars there are several with speeds

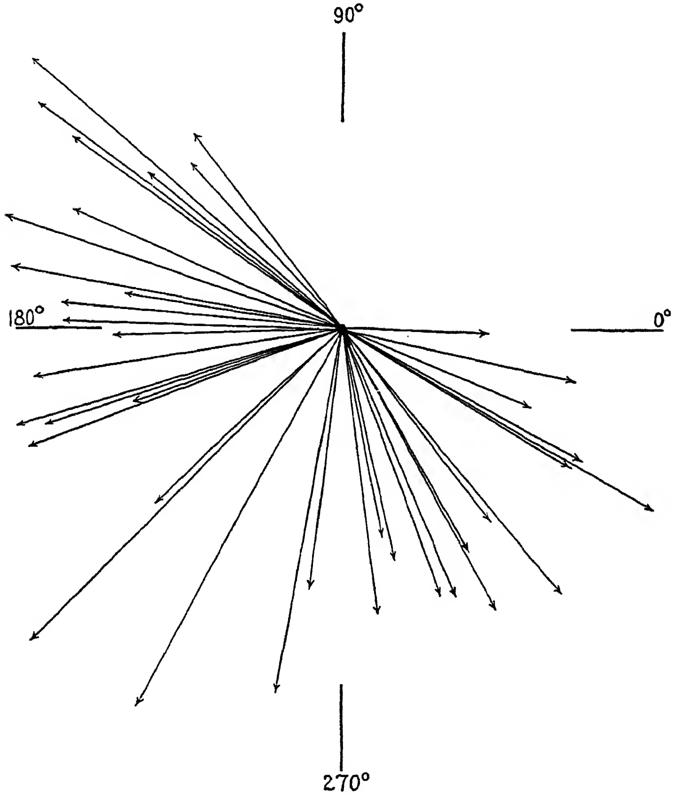

Fig. 54.—The asymmetry in stellar motions.

From data assembled by Oort for nearby stars with speeds in excess of sixty kilometers per second.

outside the normal range of ten to thirty kilometers per second. The stars with velocities in excess of sixty kilometers per second show a very peculiar distribution of the

directions of their motions. In Figure 54 we have reproduced a diagram in which the velocity arrows for the high-velocity stars within sixty-five light years of the sun are shown in projection on the plane of the Milky Way. With very few exceptions the stars are moving toward the half of the Milky Way from Sagittarius through Carina to Orion; there is not a single star moving toward the part of the Milky Way between Cgynus and Taurus.

Fig. 55.—Gustav Stromberg of Mount Wilson.

If we should try to explain the observed regularities of stellar motions in the vicinity of the sun as a consequence of the gravitational action of our nearest neighbors, we might be able to explain general star streaming, but it is hopeless to find an explanation for the observed asymmetry in the motions of the high velocity stars. The researches of Stromberg and Oort showed that the asymmetry was by no means limited to the stars near the sun. Our cube is now, however, becoming too small for comfort, so let us blow the trumpet, break through the walls, and see how the more remote stars and clusters move through our galaxy.

Galactic Rotation

The globular clusters have already proved exceedingly helpful in our attack on the general outlines of galactic structure. Let us recall again the general picture of our galaxy as presented toward the end of the preceding chapter. The sun was found well out toward the edge of a

highly flattened stellar system. The globular clusters on the other hand appeared to form a more or less spherical super-system with very nearly the same center as that of our galaxy of stars.

A stellar system cannot be highly flattened without turning around an axis at a rapid rate. We detect such rotation around an axis at right angles to the major plane in every spiral galaxy for which radial velocity measurements in the outer parts are possible. The degree of flattening of a stellar system depends to a considerable extent on the rate at which the system is whirled around the axis.

Fig. 56.—A typical spectrum of a globular cluster.

Photograph by Mayall as part of an extensive program of radial velocities of globular clusters in progress at Lick Observatory.

If we apply this reasoning to our own system we conclude naturally that our galaxy of stars must be in rapid rotation, simply because of the observed flattening, but that the globular clusters, which are arranged in a more nearly spherical system, should not share in this rotation. The study of the radial velocities of globular clusters becomes then of great interest.

The radial velocities of the globular clusters show the asymmetry effect even more pronouncedly than the stars in Figure 54. They are found to move with a speed of 200 to 250 kilometers per second toward an antapex at galactic longitude 243°. This is the same peculiar direction as that found for the nearer stars of high velocity. The work of Stromberg showed that all stars of high velocity share the same antapex, which is very nearly 90° away from the galactic center in Sagittarius.

It is most reasonable to suppose that the spherical system of the globular clusters is at rest and that the sun and most of its neighbors are whirled around the galactic center at a rate of 200 to 250 kilometers per second toward the part of the Milky Way with galactic longitude equal to 243° minus 180°, or 63°. We have first restricted ourselves to the motion of the stars that are fairly close to the sun. Apparently the average star in our sample cube rotates around the center at a rate of at least 200 kilometers per second in a direction which is at right angles to that toward the galactic center. It would seem that our cube is describing a circular orbit around the galactic nucleus.

Fig. 57.—Bertil Lindblad of Stockholm.

The first corroborative evidence comes rather surprisingly from outside our own galaxy. Together with the Magellanic Clouds, the Andromeda nebula, the spiral in Triangulum, and another half dozen similar objects, our galaxy forms some kind of a local super system. If we assume that our sun moves at a rate of 250 kilometers per second around the center in Sagittarius, we find that the relative speeds of all galaxies of our local group become small.

Lindblad, who is the originator of the theory of galactic rotation, did, however, develop it specifically to explain the observed asymmetry in the motions of the high velocity stars. Stromberg and Oort had found that all high-velocity objects move, as viewed from our sun, at a high rate of speed toward galactic longitude 243°. The cluster variables

are a typical example; their rate of speed is of the order of 100 km/sec. This motion was however measured with respect to our sun. Since our sun moves with respect to the center of our galaxy at a rate of 250 kilometers per second in the opposite direction, the cluster variables are, with respect to the galactic center, moving at a rate of 250 minus 100, or 150 kilometers per second in the same direction as the sun. The roles are reversed. The sun is now the fast moving object and the cluster variables are cast in the ignomious role of being the laggards that cannot keep up with the majority of the stars.

But, you might say, why are there not some real high velocity stars that move at a rate of 250 plus 100, or 350 kilometers per second with respect to the galactic center? We do not tolerate such stars in our galaxy. Stars in our vicinity may apparently whirl sixty kilometers faster than our sun around the galactic center, but our galaxy does not allow real speeders. The law of gravity acts the part of the motor cop on the parkway. In a flattened galaxy, such as ours, stars with velocities in excess of 300 kilometers per second are whirled out of the galaxy, sentenced for the rest of their existence to live in the Siberian wastes of intergalactic space.

Lindblad showed that the rotation of our galaxy also clears up the matter of star streaming. We supposed that the majority of the stars moved in almost circular orbits around the galactic nucleus. The observed spread in stellar motions shows, however, that this is not exactly true. Most stars move in orbits that are very nearly circular, but yet slightly elliptical in shape. The mathematical treatment of the problem is straightforward, but unfortunately it is not so simple to translate it into non-mathematical language. We shall therefore have to ask the reader to accept in good faith that the slight deviations from pure circular motion will

produce, for an observer at the sun, effects of star streaming similar to those found by Kapteyn and Schwarzschild.

According to the simplest form of the theory of galactic rotation the direction of the true vertices should point exactly toward the galactic center. The observed vertex is ten to fifteen degrees away from the direction toward Sagittarius. This vertex deviation is one of the most significant clues for a second approximation in which the irregular distribution of matter in our galaxy is taken into account.

Fig. 58.—Jan H. Oort of Leiden.

After Lindblad had presented his explanation of the observed asymmetry in stellar motions, Oort found a further proof for the general rotation of our galaxy in the radial velocities and proper motions of the stars between one thousand and ten thousand light years from the sun. Oort reasoned that it is very unlikely that our galaxy should rotate like a solid wheel. If this were so the stars would keep the same relative positions and no effects in the radial velocities would be observed. If a considerable part of the total mass of our galaxy is concentrated near the galactic nucleus, we would rather expect that the motions of the stars in our galaxy would resemble those of the planets around the sun. Venus moves faster than the Earth and the Earth in turn outruns Mars. So we may expect that the stars nearer the galactic center will generally move faster than those beyond the sun farther from the center.

Oort showed that the effect in the radial velocities would go twice through its range of values as we observe from the sun completely around the galactic circle. Figure 59 shows how this comes about.

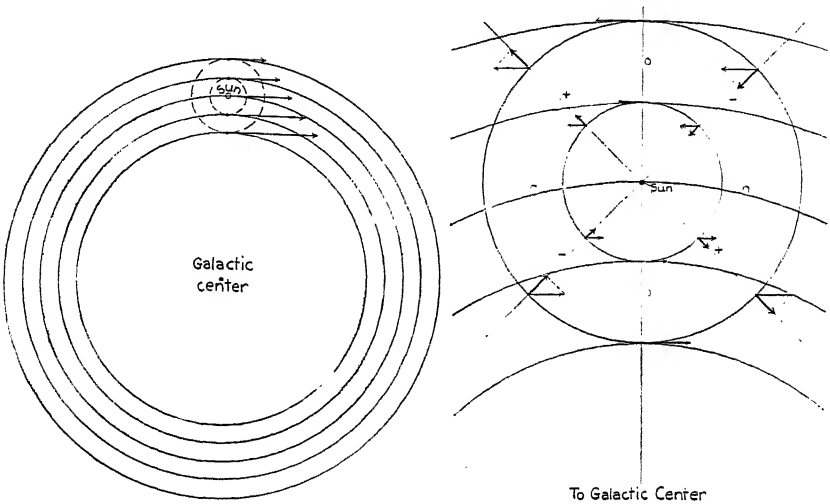

Fig. 59.—The effects of galactic rotation on radial velocities. The diagram on the left illustrates the variation of rotational velocity at various distances from the center. In the second diagram we have reproduced the region around the sun on a larger scale. The arrows represent now the velocities as seen from the sun. The radial components of these velocities show the variation of the galactic rotation effect with galactic longitude.

At four points along the circle there should be no approach or recession of the stars, due to galactic rotation, and the observed rotational effect in the radial velocities should there be zero. Along one diagonal the stars will be receding and hence should show average positive radial velocities, and along the other diagonal they should show the average negative radial velocities, corresponding to approach. The result will be, as we plot the average observed radial

velocities against the galactic longitude, a curve with a double wave, the zeros occurring at four points ninety degrees apart, one of which should be in the direction of the galactic center. It is important to note that the galactic rotation effect in the radial velocities will be largest for the most distant stars. Oort showed that for distances up to ten thousand light years from our sun, the effect progresses very nearly proportionally to the distance from the sun.

Some of our readers may wish to see the mathematical formula for this effect. If V is the expected effect, r the average distance of the stars under consideration, l the longitude of a particular star, and l_0 the longitude of the galactic center, we have the expression:

Fig. 60.—J. S. Plaskett of Victoria.

$$V = rA \sin 2(l - l_0)$$

where A is the "Oort" constant which measures the maximum effect at a standard distance.

Oort traced the effect first in the radial velocities of the O and B stars, the Cepheid variables, and the planetary nebulae. He found from the incomplete data available in 1927 that such a rotation did take place and that the center of rotation was definitely in the direction of Sagittarius.

Oort's investigations have been confirmed from many sides. Plaskett and Pearce at Victoria have obtained some very fine results from the radial velocities of the O and B stars. The planetary nebulae have been further investigated

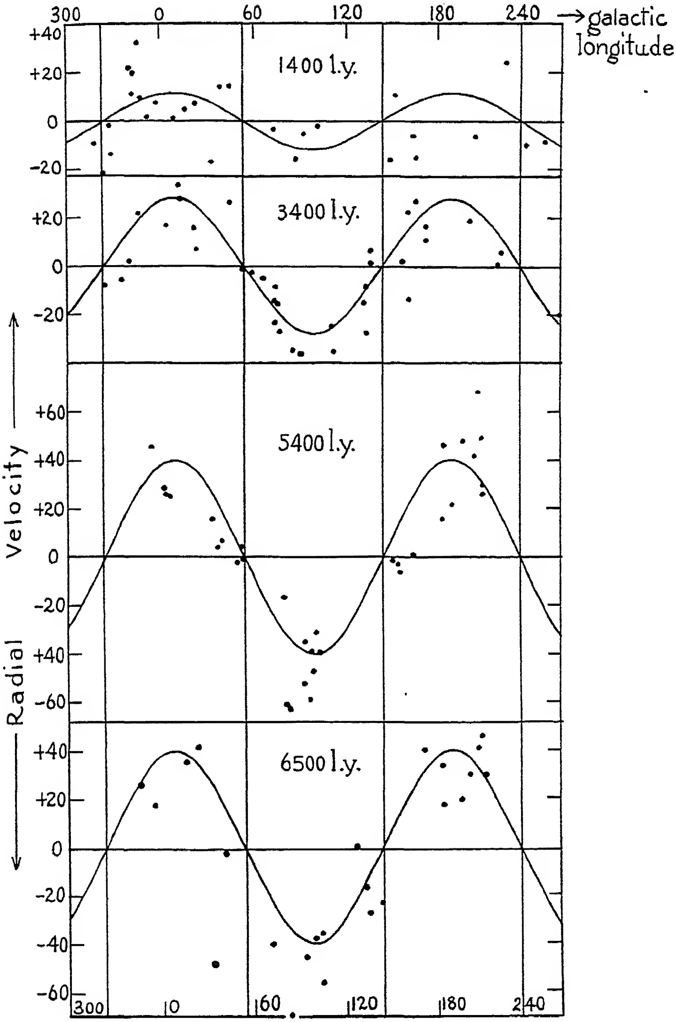

Fig. 61.—Cepheids and galactic rotation.

Measurement of the radial velocities of Cepheid variables by Joy at Mount Wilson exhibit clearly the double waves with amplitudes increasing proportionally to the distance from the sun.

by Berman and Camm, with results that indicate that these objects are so far away that Oort's theory needs to be modified. At Mount Wilson, Joy, Merrill, Sanford, and Wilson have worked on radial velocity effects in distant stars. Joy's work on Cepheids represents probably the most definite confirmation of Oort's hypothesis. There is now every indication that the Oort theory describes accurately the observed regularities in the radial motions of the stars for distances up to ten thousand light years from our sun.

The best value of Oort's constant A is between five and six kilometers per second for a distance of one thousand light years. The direction of the galactic center is apparently very close to $l_0 = 325°$.

Oort's theory predicts also an effect in the proper motions of the stars. The effect in the transverse motions reaches extreme values when the radial velocity effect is zero. We measure our proper motions, however, in seconds of arc per year and not in kilometers per second. If we go twice as far out the linear effect will be doubled, but in the observed angular motions the effect will remain unchanged. The effect in the proper motions should therefore vary only with the galactic longitude of the stars involved and not with their distances.

Unfortunately it is far more difficult to check on the effect in the proper motions than on the radial velocities. Proper motions are frequently affected by systematic errors that may be large enough to mask the rotation term. The available evidence confirms Oort's theory, but it can hardly be said to be very conclusive.

The combination of the results from radial velocities and proper motions makes possible a new determination of the distance to the galactic center. The resulting value of thirty thousand light years agrees closely with that found from the study of the distribution of globular clusters.

We can further obtain from Oort's theory an approximate value of the total mass of our galaxy. The total mass proves to be of the order of two hundred billion solar masses, of which approximately half is in the nucleus. The period of one complete revolution of our galaxy around its axis appears to be of the order of two hundred million years.

The theory of galactic rotation is a great advance in our understanding of the observed regularities in stellar motions. It has provided us with very reasonable explanations of star streaming and asymmetry and has further lead to the discovery of the Oort effects. There are however two things that we should keep in mind. Oort's picture of a smooth rotating galaxy can at best be only a very first and rough approximation to the true state of affairs in our complex Milky Way system. And second, the theory of galactic rotation is purely descriptive and does not tell us why the galaxy rotates as it does. Recent work by Lindblad and Chandrasekhar shows us we may perhaps hope to understand in the not too distant future how our galaxy came into its present state; but unfortunately we know as yet too little about the details of galactic structure.

6

BRIGHT AND DARK NEBULAE

Diffuse Bright Nebulae

Many of our readers have probably viewed the Great Nebula in Orion through a telescope. The soft greenish hue of the nebulous mass, gradually dimming toward the edge of the field, its erratic though immobile shadings, smooth and mellow in spots, hard and sharp elsewhere, together with the diamond-like scintillations of the four closely-packed stars of the trapezium, present a picture of unsurpassed beauty. No telescope has ever been able to resolve this glowing mass, and spectroscopic evidence shows that it is a true nebulous cloud of gas, shining in the transmitted glory of its central stars. What makes such nebulae shine?

The Orion nebula has a bright line spectrum in which the lines of hydrogen, highly ionized oxygen, and helium predominate. Nebulae like the Orion nebula are not self-luminous. Twenty years ago Hubble showed that a very hot star could be located in the immediate vicinity of every diffuse nebula with a spectrum similar to that of the Orion Nebula.

Fig. 62.—The Great Nebula in Orion.

From a photograph taken at Lick Observatory with the Crossley reflector.

The physical theory which explains why and how such nebulae shine is quite simple. The densities and pressures in the nebulae are so low that according to earthly standards we would consider any one of them a perfect vacuum. In our physical laboratories an atom is never left alone for any length of time; it is constantly bumping into one of its fellows or into the walls of the container. If we wish to observe the atomic processes in their majestic simplicity we shall have to turn to the diffuse nebulae, or the interstellar gas; apparently the only places where atoms are left alone enough to perform without undue disturbances.

The atoms in the nebular gas are being bombarded in a very leisurely fashion by the radiation from surrounding stars. The only light quanta that can do any real damage are those of very high frequency sent out in abundance by the white giants of spectral types *B* and *O*. Most quanta of lower frequencies will simply filter through the gas without bothering it or being bothered to any appreciable extent. If a quantum of very high frequency strikes a neutral atom it may transfer enough energy to the atom to cause the expulsion of an electron. The atom is then no longer electrically neutral, but becomes positively charged, or ionized. The electron is free and starts off by itself on a journey through interstellar space. What can happen to the electron? With its negative charge it is ready and eager to combine with any positively charged ion that is available, but it soon discovers that there are very few of these ions. Our original ion is equally hampered in its search for a free electron which would return it to the neutral state. An atom once ionized may travel for days before it encounters a free electron to neutralize its charge. In the interstellar laboratories physical processes operate in unhurried, leisurely ways. An atom inside a star, or one strutting its stuff in one of our physical laboratories on the earth, is constantly

being bumped and jostled. The atoms in the nebulae, however, live alone and like it.

Occasionally one of the free electrons will be captured by a positively charged ion. Let us suppose that a capture is made by a hydrogen ion, that is, a proton. According to modern atomic theory the captured electron can land in any one of the stationary orbits of the neutral hydrogen atom. If the capture takes place in the tightest orbit—that of lowest energy—the whole show will be over at once. A single ultraviolet quantum will then be emitted as a by-product of the capture. Frequently the free electron will be captured in one of the orbits of higher energy. The hydrogen atom cannot stay for more than a small fraction of a second in the excited state and the capture is followed immediately by the collapse of the newly created neutral atom. The electron cascades down to the orbit of lowest energy, where it will remain until the next ultraviolet quantum comes along to begin again the sequence of disruption and ultimate recombination. During the cascading process, the captured electron will go down from the orbits of high energy of the neutral hydrogen atom to the lower levels. The chances are that somewhere on the way a quantum corresponding to one of the Balmer transitions will be released. The Balmer lines in diffuse nebulae are produced during such internal adjustments in the neutral atom which follow immediately after the capture of a free electron by a proton.

Until 1912 it was generally supposed that all bright nebulae would show spectra similar to that of the nebula in Orion; i.e., brightline spectra. Then Slipher announced that the nebula associated with the Pleiades gives an absorption spectrum, very much like that of the brightest stars in the Pleiades cluster. It was later found that many other nebulae behaved in a similar fashion. There are

therefore two kinds of bright nebulae, one with bright emission spectra, the other with dark line spectra similar to those shown by the majority of the stars.

Fig. 63.—Edwin P. Hubble of Mount Wilson.

Hubble found that emission spectra nebulae are always near very hot stars with spectral types *O*, *B*0 or *B*1. The second class of nebulae, those with absorption spectra, are associated with cooler stars. The term reflection nebulae was applied to this group after it was shown that the spectrum of the "responsible" star and that of the nebula were the same. The lack of emission spectra for these nebulae is explained by the absence of a sufficient supply of ultra-violet radiation in the light emitted by the relatively cool stars.

Dark Nebulae

If a cloud of gas and dust is present in interstellar space it will not appear as a diffuse nebula unless there is a bright star in or near the cloud. The exciting stars and nebulous clouds are generally not physically connected and it is hardly surprising that we find many interstellar clouds that are not near a suitable star. Such clouds will, however, absorb and scatter the light from the stars beyond them and they will be distinguishable as dark nebulae against the bright background of the Milky Way.

Dark nebulae are not conspicuous objects for visual observers. They are uninteresting regions devoid of stars—

or with fewer stars than normal—and an observer will pass them by in favor of the fields rich in stars. Sir William Herschel was the first astronomer who seriously considered the implications of the vacancies along the Milky Way, and it was also Sir William who noticed that these vacancies

Fig. 64.—Messier 8 and the Trifid Nebula.

The diffuse nebula Messier 8 (top) and the Trifid Nebula, photographed with the 24-inch Bruce camera at the Boyden Station of the Harvard Observatory.

occurred frequently in the vicinity of bright nebulae. It was not until a century after Sir William's observations that Barnard and Wolf succeeded in proving from their Milky Way photographs that many vacancies were caused by obscuring clouds rather than by holes in the Milky Way.

We have reproduced in this book several photographs of bright diffuse nebulae. All these photographs not only show the presence of bright nebulosity; but the numerous irregularities in the star distribution also suggest that, associated with it, is much non-luminous material. Let us

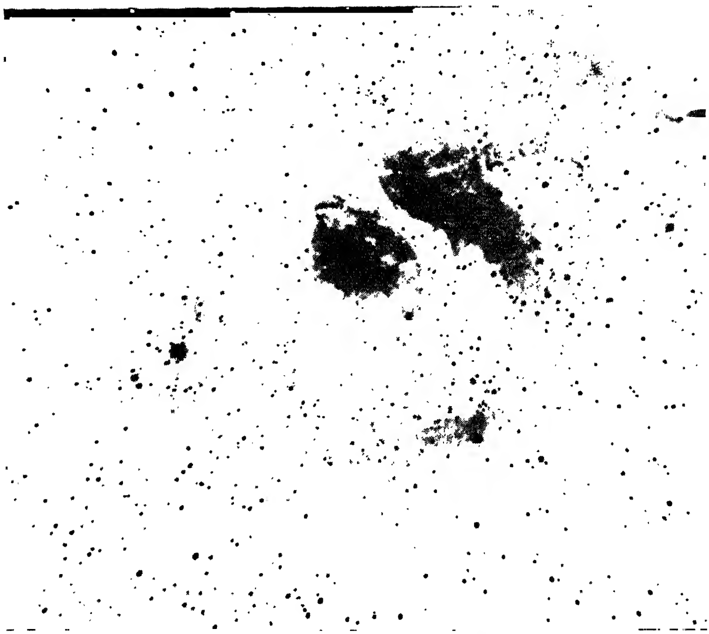

Fig. 65.—The Diffuse Nebula Messier 8.

From a photograph by Struve and Elvey with the 82-inch reflector at McDonald Observatory.

take the photographs of Messier 8 (Figure 64 and Figure 65) as a first example. Superimposed upon the bright mass of nebulosity we find many small dark spots, some of which would almost seem like defects in the photographs. These spots are always seen in the same position and they can only be interpreted as small obscuring clouds.

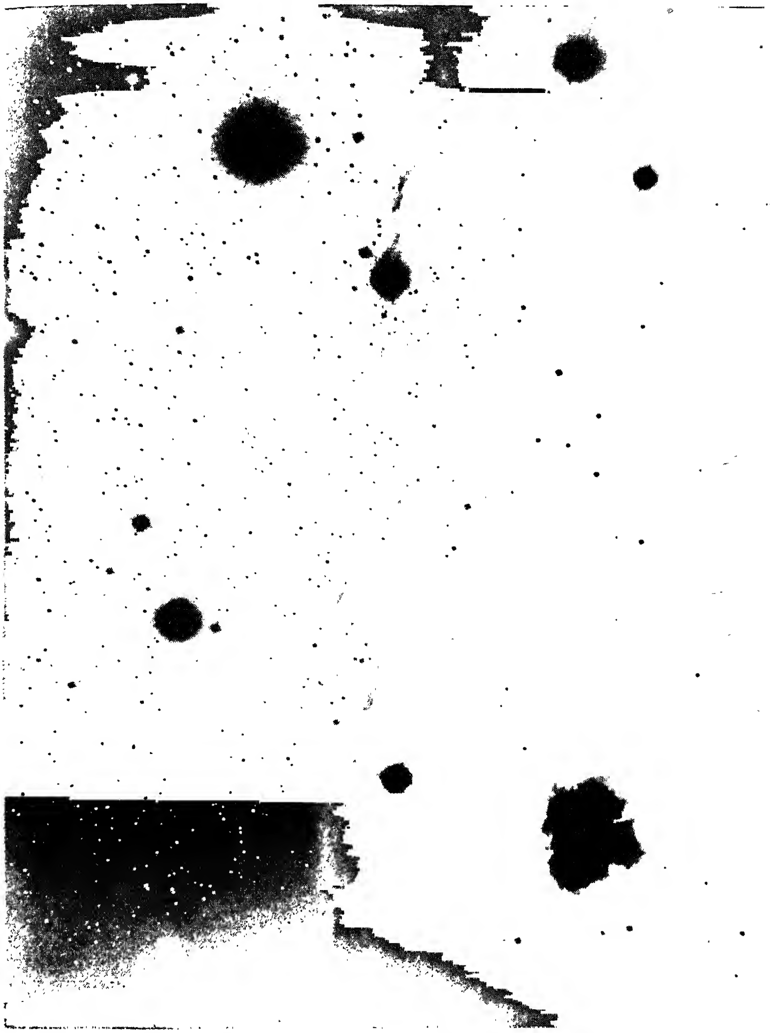

Fig. 66.—The Horse-head Nebula in Orion.

From a photograph taken by John C. Duncan with the 100-inch reflector at Mount Wilson.

Another instance of a real association between bright nebulosity and an obscuring cloud is shown in the photograph of the Horse-head nebula in Orion (Figure 66). The ectoplasmic glow around the horse's head emanates from the bright nebulosity. The horse's head is a part of the large dark nebula that covers most of the lower half of the picture. If the dark nebula suggests an ominous thundercloud, the bright nebula is its sunlit edge. The photograph of the Horse-head nebula shows clearly the power of the dark nebula to absorb the light of the stars beyond it. If we compare the number of stars in two squares of equal size, one to the left, the other to the right of the horse-head, we count at least ten times as many stars in the first square as in the second square. One can have little doubt about the power of this particular dark nebula to dim the light of the stars that lie behind it.

The photograph of the region in Orion (Figure 67) is another illustration of the association between bright and dark nebulosity. The scale of the photograph is such that the bright nebula in Orion, which is so familiar from photographs taken with large reflectors, covers only a small area near the center of the plate. One of the most striking features is that there are on the average more stars per unit area near the edge than there are in the central portions surrounding the bright nebula. The famous diffuse bright nebula in Orion is part of an extended dark nebula that covers an area which is equivalent to fiftv times that covered by the full moon.

The southern Coalsack is one of the most striking dark nebulae in a region devoid of bright nebulosity. Largely because of the contrast with the brilliant Milky Way surrounding it, the Coalsack appears to the visual observer as an intensely black cloud. Telescopic observations will readily reveal the presence of numerous faint stars in the

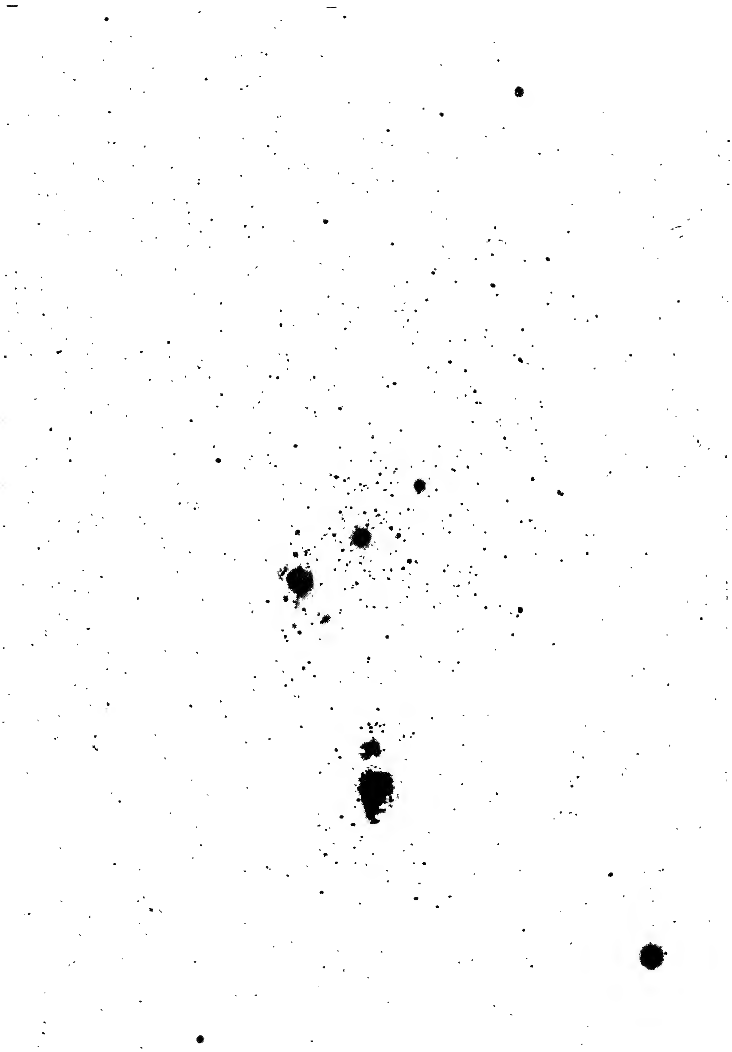

Fig. 67.—The Region of the Orion Nebula.

Stars and nebulae in Orion photographed by Tabor with the 10-inch Ross camera of the Cook Observatory.

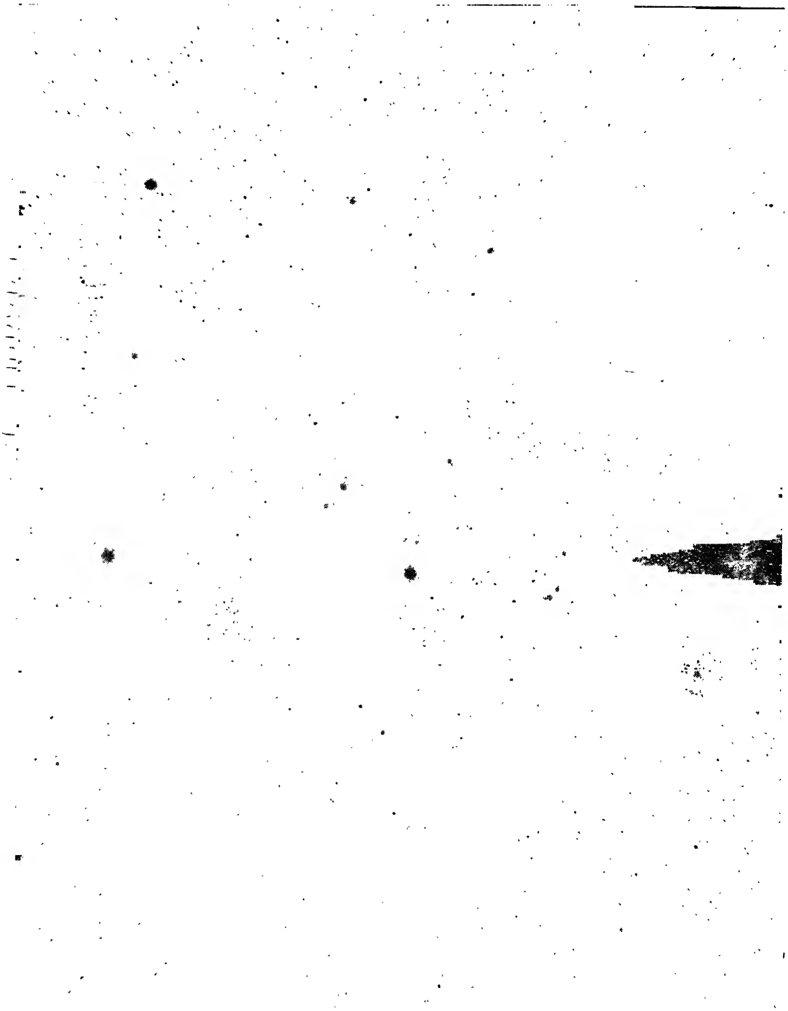

Fig. 68.—The Coalsack and the Southern Cross.

From a photograph by Margaret Harwood at the Boyden Station of the Harvard Observatory.

apparent inky darkness of the Coalsack. A long exposure photograph, such as that reproduced in Figure 68, shows that there are still on the average one-third as many faint stars in the Coalsack as in an adjacent area of the same size. It is not really so black as at first it appeared. In the same way, the sun spots appear black against the sun's disk

Fig. 69.—The North America Nebula.

From a photograph by Barnard at Mount Wilson with the 10-inch Bruce camera of the Yerkes Observatory.

although they are actually very bright. The Coalsack nebula stood for many years as the finest example of a dark nebula free from bright nebulosity. But few such records are allowed to stand. In 1938 a minute little flare of bright nebulosity in the Coalsack was found by Lindsay.

Fig. 70.—E. E. Barnard of Yerkes.

Our presentation of dark nebulae would not be complete without a reproduction of some of Barnard's photographs. Figure 69 shows the North America Nebula, so named by Max Wolf of Heidelberg. The photograph gives a striking illustration of the association between bright and dark nebulosity. The "United States" is a conspicuous bright nebula, the "Gulf of Mexico" is one of the densest portions of the surrounding dark nebula. From the large numbers of faint stars that shine through the bright nebula, it is apparent that the bright nebulosity is more transparent than the surrounding dark portions.

Another striking photograph by Barnard is reproduced in Figure 71. The dark nebula near the star Rho Ophiuchi is probably part of the giant dark nebula in Ophiuchus, which according to the evidence from the distribution of stars and faint galaxies covers an area of one thousand square degrees. The great body of the nebular mass lies from five to twenty degrees north of the galactic circle and lacks the background of faint stars to render it conspicuous. The low latitude "tentacles" of the Ophiuchus nebula, however, are seen projected against some of the richest

Fig. 71.—The Dark Nebulae near Rho Ophiuchi.

From a photograph by Barnard at Mount Wilson with the 10-inch Bruce camera of the Yerkes Observatory.

portions of the Milky Way and the nebula near Rho Ophiuchi is one of these tentacles.

What can we learn about the extent, distance and composition of a dark nebula? Information on the first two

points can be obtained from star counts in and around a dark nebula. The counts for two areas of similar size, one in the dark nebula, the other in a neighboring unobscured region, will generally agree for the brighter stars. As we count to fainter apparent magnitudes we soon come to a point where the counts in the obscured area fall below those for the comparison area. The percentage deficiency will generally increase as fainter stars are included in our

Fig. 72.—Max Wolf of Heidelberg.

Fig. 73.—Antonie Pannekoek of Amsterdam.

counts, but will finally become very nearly constant. The magnitude for which the deficiency begins to be noticeable gives us some idea about the approximate distance of the dark nebula; the percentage deficiency for the faintest magnitudes is a good measure of the total obscuration caused by the cloud.

Wolf was one of the first astronomers to realize the value of star counts for the study of dark nebulae. Statistical methods for the analysis of such star counts were developed by Pannekoek. The large spread in the absolute magnitudes of the stars of all kinds that make up general star-counts

renders it difficult to compute accurate distances of dark nebulae, but Pannekoek's method of analysis tells us at least whether the absorbing cloud is at two hundred, six hundred or fifteen hundred light years from the sun. Pannekoek showed further that counts to faint limits gave very precise information on the total absorption of the nebulae.

Fig. 74.—Carl Schalén of Upsala.

The southern Coalsack, for example, is caused by a dark cloud at roughly three hundred light years from our sun. That is right next door as galactic distances go. The total absorption of the cloud averages a little more than one magnitude, but in some special objects it is as high as three magnitudes.

In the more refined studies of dark nebulae, the spectra and colors of faint stars figure prominently. The extent to which the starlight will be reddened in its passage through a dark nebula depends almost entirely on the average size of the dust particles in these nebulae. Seares and Hubble had shown twenty years ago that stars embedded in bright nebulosity are generally reddened. The first extensive study of the effect of a dark nebula on the colors of faint stars was made ten years later. The Swedish astronomer Schalén showed that dark nebulae affect the color of starlight that passes through, but that the percentage of reddening is very slight. Schalén concluded that the particles which are the most effective absorbers are tiny dust specks with diameters of the order of three one-millionth of an inch. Schalén made the apparently rather reasonable assumption

that these tiny dust specks are metallic, probably compounds of iron, zinc or copper.

Struve and his associates at Yerkes Observatory have studied the scattered light produced by some dark nebulae. We have rather carelessly applied the term "absorbing clouds" to the dark nebulae. In reality the process that takes place is more nearly one of scattering. When the light from a star strikes a tiny particle in the dark cloud the light is partly "absorbed"—or, in other words, absorbed and later re-emitted in the form of unobservable "heat" radiation—but the rest of the light is reflected and scattered into space in all directions. The nebula should therefore be faintly visible in the glow of the scattered light. It is difficult to measure this faint glow, and even more difficult to interpret it, but the observations that have so far been made, in particular those of Greenstein and Henyey, indicate that the fraction of the incident light that is scattered is quite considerable. Apparently the particles in dark nebulae are more effective scatterers than metallic specks could possibly be. The suggestion has been made that the observed properties agree with what we should expect from tiny ice crystals. Perhaps the dark clouds of space are more nearly like our hail or snow clouds than we would off-hand have supposed!

7

THE INTERSTELLAR GAS

The Discovery of Stationary Lines

THE DISCOVERY OF THE INTERSTELLAR GAS GOES BACK TO 1904 when the German astronomer Hartmann showed that the absorption *K*-line of ionized calcium (wave length = 3933 angstroms) in the spectrum of the star Delta Orionis behaved in a very peculiar fashion. Delta Orionis is a blue star with a *B*0 spectrum and was recognized to be a spectroscopic binary. Hartmann found, however, that the wave length of the *K*-line did not vary at all in the course of the binary period. The hydrogen and helium lines in Delta Orionis were broad and fuzzy, but its *K*-line was sharp and distinct. Hartmann referred to the line as the "stationary" calcium line.

Stationary calcium lines were abundantly discovered in the spectra of many other early type stars. In 1919 Miss Heger and Wright at Lick Observatory found that the spectra of some early type stars have strong stationary sodium lines, in addition to their stationary calcium lines. In all cases such lines were found to be sharp and distinct.

The interstellar origin of these absorption lines was first suggested by V. M. Slipher in 1909, but his suggestion

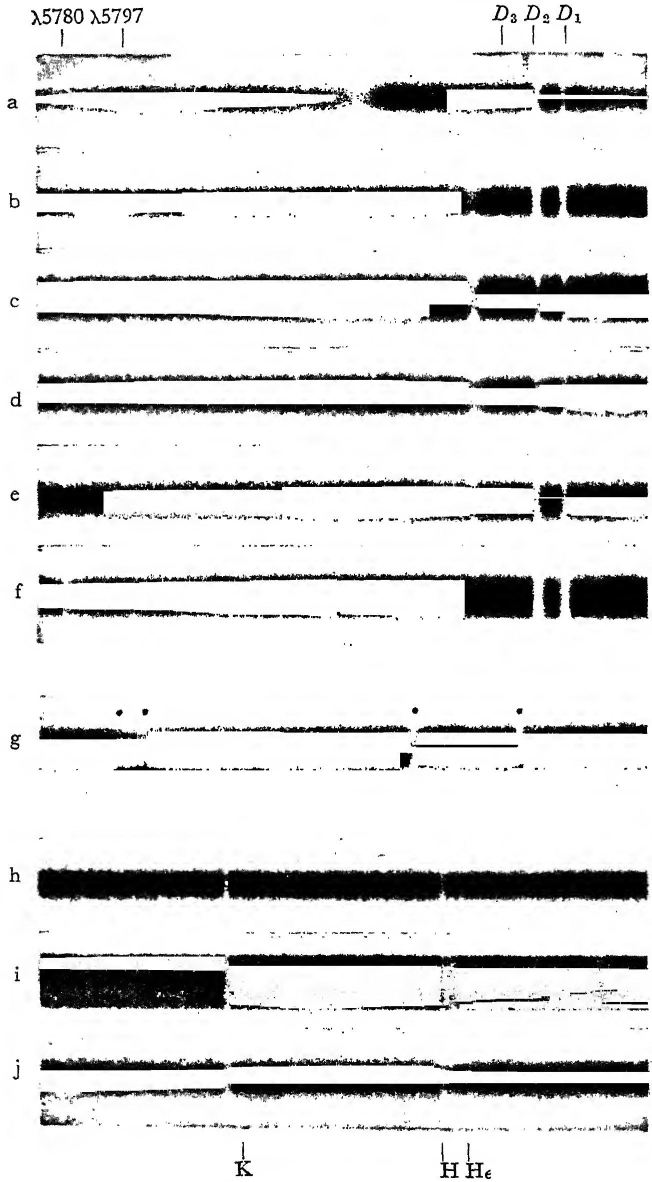

Fig. 75.—For descriptive legend see page 129.

unfortunately did not receive the attention that it deserved and Slipher's views were not generally accepted until more than fifteen years later. It was thought at first that the stationary lines originated in the immediate vicinity of the stars in whose spectra they were found. The researches of Plaskett and of Struve proved that this explanation was incorrect. Theoretical investigations, especially those of Eddington and Rosseland, showed further that stationary lines of calcium would naturally be observed if any interstellar gas were present. The total evidence left little doubt as to the interstellar origin of the stationary lines and from 1930 on they are generally referred to as interstellar lines.

Recent researches of the interstellar gas have dealt partly with its composition and the physical conditions in the gas and partly with the role of the interstellar gas in our rapidly rotating galaxy.

The Physics of Interstellar Gas

Adams and Dunham at Mount Wilson have demonstrated the presence of absorption lines from neutral calcium and potassium and ionized titanium, in addition to the lines of ionized calcium and neutral sodium that had been found earlier. Merrill, also working at Mount Wilson, has found some broad lines or bands of interstellar origin for which accurate identifications are still lacking. Dunham noted three sharp interstellar lines in the blue-violet part

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Fig. 75.—Mount Wilson spectra showing lines of interstellar origin.

In spectra *a* to *f* the lines D_1 and D_2 are due to interstellar sodium. Note also the faint interstellar lines at $\lambda = 5780$ and $\lambda = 5797$. The line D_3 is of stellar origin. Spectrum g shows near the second dot from the left the interstellar band at $\lambda 6284$. Spectra h to j show the interstellar H and K lines. Note the sharpness of these lines in comparison with the stellar Hϵ. Photographs by Merrill and his associates at Mount Wilson.

of the spectrum that remained unidentified until quite recently. These lines have now been identified by McKellar as probably arising from molecular transitions in CH, CN and NaH. The identification of the lines due to CH led to the prediction of some further interstellar lines that have since been photographed at the Mount Wilson Observatory.

The observations on interstellar gas all fit into a smooth theoretical picture, if we develop our theory along the same lines as that for the diffuse nebulae with bright line spectra. Again we meet with a very extended cloud of gas that is not self-luminous. The gas density is, however, roughly only one per cent of that in the Orion nebula, but this low density prevails everywhere near the galactic plane. The interstellar gas is ionized to a considerable degree. The ionizations are caused when a rare ultraviolet quantum strikes a neutral atom in interstellar space. Just as in the diffuse nebulae with emission spectra, the free electron and remaining ion set out on their search for a mate with an opposite charge. They soon find that their chances for recombination are much less than in an average diffuse nebula, but ultimately an ion will again meet with a free electron and the union will be celebrated in much the same fashion as in the diffuse nebulae.

Fig. 76.—Paul W. Merrill of Mount Wilson.

How do the observed interstellar absorption lines come into existence? The percentage ionization of the interstellar gas is controlled by the stellar light rays in the far ultra-

violet and the visible rays from the stars have no effect on conditions in the gas. Some of the visible light rays of just the right wavelength may be scattered by the atoms or ions of the interstellar gas (the electrons have not much effect). Suppose we take the example of an ionized calcium atom in interstellar space. While it is patiently waiting for a free electron to join it (or as the occasion may be, for a second short wave quantum to tear off a second electron from its outer shell) it can do some tricks of its own. If a quantum of light with a wave length of 3933 Angstroms happens to come along, it can excite the once ionized calcium atom in a mild way and lift one of its electrons temporarily to a level of higher energy. Unfortunately the atom can only stay in that blown-up state for something like a ten-millionth of a second before the electron of the nuclear entourage is forced back to its original low level. The energy that was originally absorbed is thereby released again, but the quantum of wave length 3933 Angstroms will pass on in a direction that differs generally from that in which it was going before the impact with the calcium ion.

Now suppose that we are looking at the spectrum of a certain star and that there is ionized calcium between that star and us. The interstellar ions will absorb and scatter many of the quanta of wavelength 3933 Angstroms that would otherwise have reached our spectroscope, and a dark line will appear at that wave length in the spectrum of the star.

Dunham, Struve, B. Stromgren and Spitzer are the most recent investigators of the physics of the interstellar gas. All are agreed that hydrogen is by far the most abundant of the elements in interstellar space. Sodium follows, but it is probably relatively so rare that a chemist would have great difficulty in detecting sodium by a chemical analysis of an average sample of the interstellar gas, if such were

obtainable. There is still some uncertainty about the percentage ionization of the interstellar hydrogen. Most of the hydrogen is ionized in the parts of our Milky Way where there are many blue-white stars rich in ultraviolet radiation. Strömgren suggests, however, that even in the galactic plane there may be large volumes of space where the nearest star rich in ultraviolet light is so far away that there are not enough short wave quanta left to strip the hydrogen atoms of their outer electrons. In such regions, the hydrogen will not be ionized.

Fig. 77.—Otto Struve of Yerkes and McDonald.

The average hydrogen densities that have so far been found are all surprisingly large; at least 90% of the interstellar stuff seems to be free hydrogen atoms. Interstellar dust particles and meteoric particles are apparently contributing only a small fraction to the total weight of interstellar matter.

It is unsatisfactory to have to imagine all this interstellar hydrogen without ever having direct evidence for its existence. The interstellar absorption lines produced by hydrogen are in the far ultraviolet part of the spectrum where the transmission of our earth's atmosphere is about nil. The Balmer lines of hydrogen will not appear in the interstellar absorption spectrum since they are produced by absorption in an atom that is already excited to the second energy level. An undisturbed atom will remain for only a very small fraction of a second in the excited stage and the probability that one of the few quanta of the right wave

length will come along just at that moment is very small. Our only hope lies in the possibility of observing the glow given off by the hydrogen during the occasional captures of electrons by the free nuclei. The free electron will often be captured in a high atomic level and Balmer quanta may be emitted as the electron cascades its way down to the peace and quiet of the lowest energy level. It is reassuring to know that Struve and his collaborators at the McDonald Observatory have actually succeeded in photographing the capture spectrum of interstellar hydrogen. They have observed faint emission spectra, that show lines of hydrogen and other elements in many places along the Milky Way.

Galactic Rotation and the Interstellar Gas

The interstellar gas partakes in the general rotation of our galaxy. This fact has been established by the researches of Plaskett and Pearce at the Dominion Astrophysical Observatory. Shortly after Oort had suggested that the radial velocities of distant stars should vary in a double sine wave according to galactic longitude, Plaskett and Pearce undertook to measure the radial velocities of several hundred faint, and hence distant, early-type stars. We have already told the story of their successful check of the theory of galactic rotation, but it seemed more appropriate to save the results of their measurements of the interstellar lines until the present chapter. The interstellar *K*-line was measurable on many of the spectrograms of Plaskett and Pearce. When the radial velocities determined from the measurements of the interstellar *K*-line were plotted against the galactic longitude of the stars, the resulting plots showed very clearly the familiar effects of galactic rotation. The striking difference was that the range of the double wave for the stars was approximately twice the range for the velocities from the *K*-line. The conclusion that Plaskett

and Pearce drew from their curves was that the interstellar *K*-line in a given star yielded on the average a radial velocity corresponding to the half-way point between the star and the observer.

The work of Plaskett and Pearce would seem to suggest that the interstellar calcium is distributed uniformly near the galactic plane. Some of the work of Struve and recent researches at Mount Wilson and Victoria have revealed the presence of an irregular regional distribution. From an analysis of the best available data on intensities and radial velocity shifts of interstellar lines, Merrill and Wilson conclude that some of the interstellar gas clouds have diameters of the order of 2000 light years. These clouds of gas are, so far as we can tell, not identical with the large dark nebulae.

8

THE GENERAL HAZE

WE HAVE IN OUR SEARCH FOR INTERSTELLAR MATERIAL paid much attention to the obscuring clouds. What about the regions where faint stars shine in great numbers and where there is no direct evidence for the presence of intervening cosmic dust? We have learned to expect along the Milky Way the tell-tale absorption lines from the interstellar gas. But the atoms of hydrogen, calcium, and sodium can only absorb light of certain very special wavelengths and the presence of the gas will not lead to any general scattering or reddening of the light of distant stars. If we find scattering or reddening effects for distant objects outside the obvious obscuring clouds we shall have to leave room on our census blanks for a general haze of cosmic dust. There seems today no doubt of its existence.

Faint Galaxies and the Haze

If we photograph any region of the sky that is at least twenty-five degrees away from the galactic belt we shall generally find some images of faint spiral or elliptical nebulae on our plate. We refer to these as "galaxies" because they are separate stellar systems, some of which

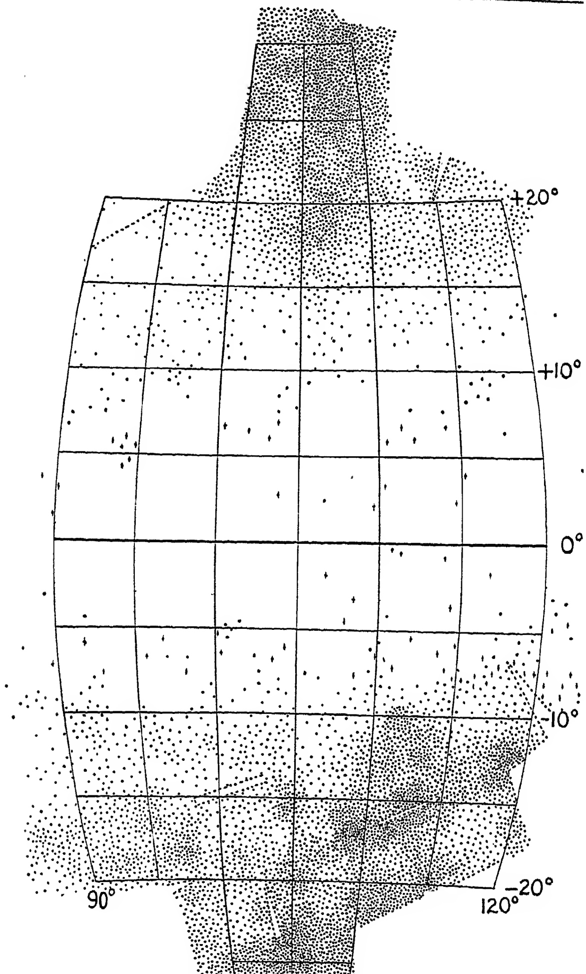


Fig. 78.—Faint galaxies and galactic absorption.

The distribution of faint galaxies in Perseus and Cassiopeia demonstrates the presence of absorbing material along the galactic belt. Diagram by Shapley and Miss Jones.

are probably not unlike our own Milky Way system. They begin to appear on one-hour plates with a ten-inch refractor; a three-hour exposure with a sixteen or twenty-four inch telescope will show sometimes hundreds of these galaxies. They appear in abundance on all regular photographs with large reflectors taken outside of the Milky Way plane.

If we photograph regions along the band of the Milky Way, even long exposure with the most powerful telescopes will not bring out any of these nebular images. What does this mean? Can it be that there are no faint galaxies in those directions or are they cut off from our view by a general interstellar absorption? There can now be little doubt that the haze is to blame. The universe of galaxies has already been explored to distances of 500,000,000 light years and it would simply be too presumptious to assume that our home-galaxy with its diameter of scarcely 100,000 light years could somehow determine the whereabouts of its fellow-galaxies. There are probably distant galaxies in all directions. Those along the galactic circle are hidden from our view by the interstellar material.

Now that we recognize its presence we shall like to know on the average how much the light of a star in the Milky Way at a distance of, say, five-thousand light years is dimmed. The most dependable "averages" have been derived from Joy's observations of the radial velocities of Cepheid variables and from Trumpler's data on galactic clusters.

Cepheids and Clusters

Joy has measured radial velocities for 156 Cepheid variables. The average apparent magnitude was known for each of these stars. We have already seen in Chapter 4 that their average absolute magnitudes can be found from the

periods of the light variation with the aid of the period-luminosity relation. In the absence of absorption the basic formula that relates apparent and absolute magnitude and distance reads: (See Chapter 2)

$$M = m + 5 - 5 \log r$$

If the light of a star is dimmed by interstellar absorption to the extent of P magnitudes the formula becomes:

$$M = m + 5 - 5 \log r - P$$

We can change this around a bit and with m, M and r known it gives us:

$$P = (m - M) + 5 - 5 \log r.$$

We know for each star $(m - M)$ and if we could only somehow find r we could then determine P, the amount of the absorption. We cannot find r, the true distance, for a single star but if we have the radial velocities of a group of stars with similar values of $(m - M)$, we can at least obtain some average value for the distance and hence for the total absorption at that distance.

Let us take for example the 34 stars, with an average value of $(m - M)$ equal to 12.5, that have been treated as one group in Joy's analysis. The radial velocities of these stars show clearly the variation with galactic longitude required by Oort's formula with the double-sine wave; $V = rA \sin 2(l - l_o)$ (See Chapter 5). From the observed maximum range we can deduce that

$$rA = 38.9$$

and with Joy's value

$$A = 20.9 \text{ km/sec per 1000 parsecs}$$

we find for the true mean distance of these stars

$$r = 1860 \text{ parsecs.}$$

We should emphasize here that this estimate of distance is no way affected by the dimming from the general haze.

According to the formula for the total absorption at that distance we have

$$P = 12.5 + 5 - 5 \times 3.27,$$

or $P = 1.2$ magnitudes. The corresponding distance of 1860 parsecs is of the order of six thousand light years. From our rough estimate for those 34 stars we find that the average amount of absorption is of the order of one magnitude per two thousand light years.

Our method is only approximate and neglects certain small statistical corrections that should be applied in a rigorous treatment. Joy's analysis from all 156 stars suggests a slightly larger value for the average coefficient of absorption, but our value happens to agree exactly with that derived quite recently by Wilson from a re-discussion of Joy's data.

The first dependable average value for the coefficient of scattering was given by Trumpler in a classical paper published in 1930. Trumpler noticed in his work on galactic clusters that the distances computed from apparent brightnesses came out smaller for the distant clusters than the distances computed from the observed diameters. Trumpler showed that the two could be reconciled if a coefficient of scattering of one magnitude per 5000 light years was assumed.

Other researches have led to average coefficients of scattering that are either equal to those given or slightly larger. In the light of all available evidence it would seem that the average coefficient will hardly exceed 1.5 magnitudes per 5000 light years near the galactic plane.

It is now time that we remember that variety is the keynote to Milky Way structure. It is all right to compute

averages, but we know that such averages may not at all represent conditions for a particular section of the Milky Way. There are hardly enough Cepheids or clusters to apply Joy's or Trumpler's methods to small sections of the Milky Way.

Space Reddening

The most promising method which applies to small regions of the sky is that in which the reddening of the light of distant stars is taken as a measure for the total amount of dimming at various distances. We have already seen in Chapter 5 that some distant star clusters are strongly reddened by the scattering effects of the general haze. Another striking instance of interstellar reddening is shown in Figure 79 where we have reproduced two photographs taken by Baade with the Mount Wilson 100-inch reflector. The top photograph was taken on a blue-sensitive plate, the other on a plate sensitive to the yellow and red region of the spectrum. The two prints have been matched so that images of an unreddened *F7* star would be equally big on both prints. The large excess of stars on the red plate as compared to the blue is excellent proof for the presence of considerable space reddening. The plates were centered on a region within five degrees of the direction toward the galactic center.

How can we measure the interstellar reddening in a qualitative way and what deductions can we make from such measurements? The principle of the method is quite simple. From the relative intensities of the stellar absorption lines we can estimate the spectral type of any star. Next we measure the color index of the star by whatever method happens to be most convenient. The difference between the observed color index and that predicted for the spectral class of the star gives its color excess, which measures

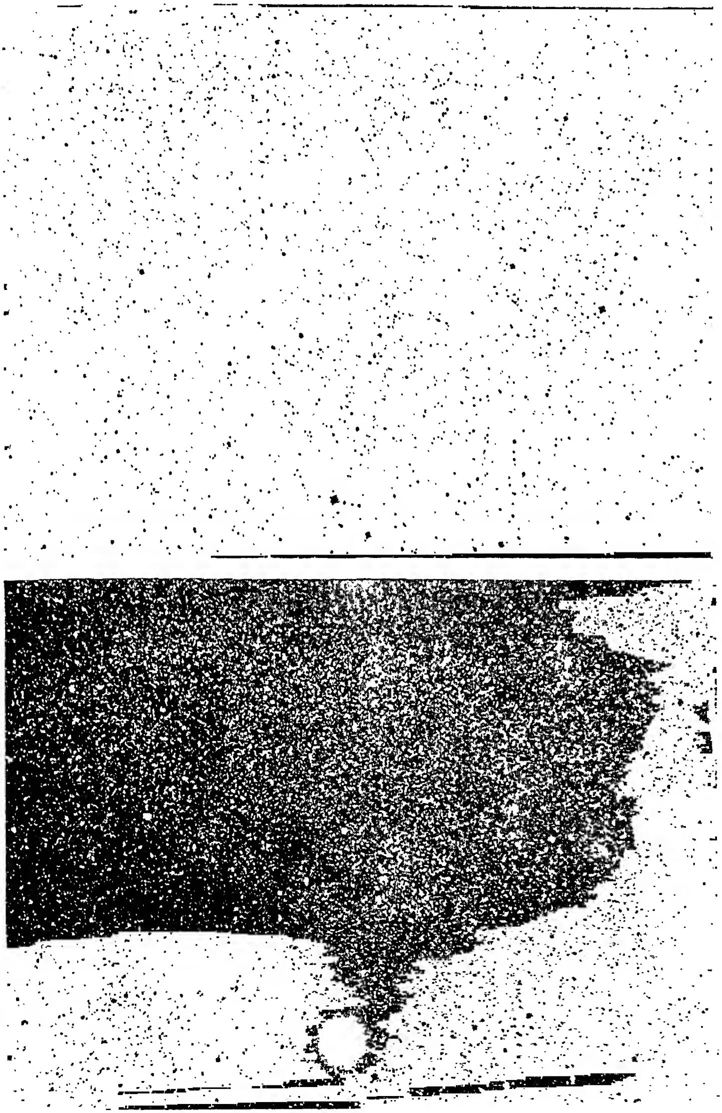


Fig. 79.—For descriptive legend see page 142.

directly the interstellar reddening. The color excess is a fair measure for the total amount of interstellar haze between the star and the observer.

The first attempts to study the reddening of the light of distant stars were made by Kapteyn and his pupils more than thirty years ago. The results were however uncertain because of a lack of suitable standards for comparisons. In 1920–22 Sears and Hubble found the first undisputable indication for the presence of space reddening in a study of the colors of the stars embedded in nebulosity. All but one of forty stars that were examined were found to be distinctly reddened. Trumpler's paper on galactic clusters and interstellar absorption, published in 1930, stimulated further color research and during the past decade numerous color studies have been made. There is great variety among the techniques that have been employed. Photo-electric measurements through two filters of different color sensitivity have yielded by far the most accurate colors, but spectrometric techniques and straight photographic com-

Fig. 80.—Joel Stebbins of Wisconsin and Mount Wilson.

Fig. 79.—Space reddening toward the galactic center.

The upper photograph shows an exposure on a blue-sensitive plate of a region within five degrees of the galactic center. The lower photograph shows that same region with comparable exposure on a red-sensitive plate. Both plates were taken by Baade with the 100-inch reflector at Mount Wilson.

parison on plates sensitive to different wavelengths have also yielded valuable results.

Stebbins, Huffer and Whitford at the University of Wisconsin and the Mount Wilson Observatory have determined photo-electrically the colors of 1332 *O* and *B* stars along the galactic circle. Because of their high intrinsic brightness, faint *B* and *O* stars are very distant objects and they are therefore quite suitable for work on space reddening. Highly reddened stars prevail in some sections of the Milky Way—in particular for the region of the galactic center—while the observed color excesses are small for

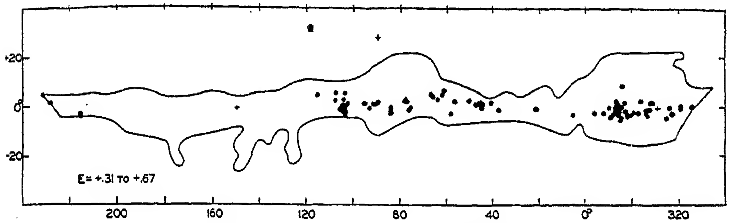


Fig. 81.—Highly reddened stars.

The distribution along the Milky Way of stars with color excesses of the order of half a magnitude. Data from Stebbins, Huffer and Whitford.

other parts. Figure 81 shows the galactic distribution of some of the most reddened stars found in this survey. The total photographic absorption for a star with a color excess of half a magnitude in Stebbins's color system is probably well in excess of four magnitudes. The stars in the diagram are therefore without exception very much affected by interstellar obscuration. Apparently no highly reddened *B* stars occur in the interval in galactic longitude between 120° and 210°, the region away from the galactic center, but they are very numerous for the region between longitudes 320° and 0°, which includes the galactic center.

Stebbins' survey is by far the most accurate color-survey that has yet been published. The importance of

color studies for galactic research is so evident that it is not surprising that many other astronomers are devoting their time and energy to this type of research. Among the most significant color studies of recent years are those on the colors of faint stars in distant clusters by Trumpler and his associates at Lick Observatory and by Cuffy working at the Harvard, Steward and Link Observatories. If colors and spectral types, or even colors alone (provided that they reach faint enough stars!), are known for a star cluster we can make not only a fair estimate of its distance, but also obtain a value for the color excess at that particular distance. Since many of the galactic clusters are at distances of more than 10,000 light years from our sun, we can obtain from them information about obscuration at great distances.

Globular clusters have also come in for their share of attention. Stebbins has measured the color indices for many globular clusters; some very reddened clusters were found in the vicinity of the galactic center. The photographs in blue and red light by Baade at Mount Wilson (Figure 82) show that near the galactic center some of the distant globular clusters are practically invisible on the blue-sensitive plates, but are quite conspicuous when photographed in red light. The space reddening for these particular objects must be very great indeed.

It is important for the detailed study of the absorption characteristics of a given section of the Milky Way that enough individual colors should be available to make possible the subdivision into small areas over which the obscuration will not vary appreciably. The total number of photoelectric colors is unfortunately still rather small in comparison with the total area covered by the Milky Way. If we think of Stebbins's 1332 stars as being distributed over a zone five degrees in width on either side of the Milky Way, we find on the average about one measured color excess

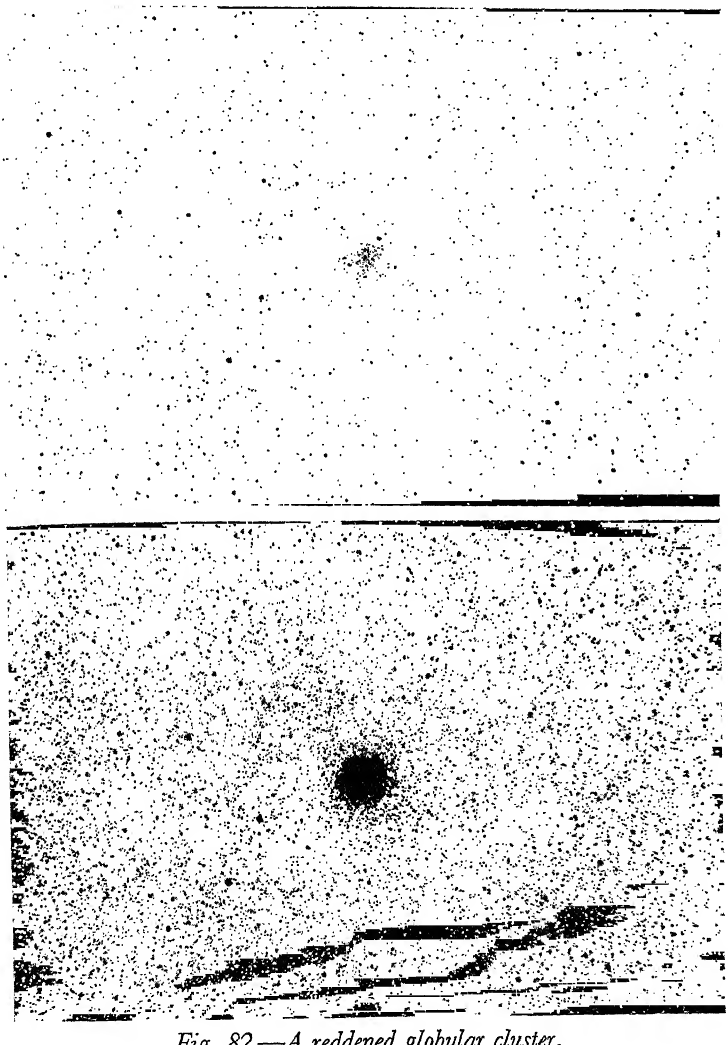


Fig. 82.—A reddened globular cluster.

The upper photograph shows an exposure of N.G.C. 6553 on a blue-sensitive plate, the lower photograph an exposure of comparable length on a red-sensitive plate. Both plates were taken by Baade with the 100-inch reflector at Mount Wilson.

for every two square degrees. That number may be sufficient for a fairly uniform region, but in many places the Milky Way is so spotty that we need many more stars. For some sections of the Milky Way the wholesale measurement of the colors of thousands of faint stars is the only way toward a solution of the absorption problem. Astronomers are fully aware of the need for faint spectra and colors. Cooperation between American, Dutch, and German astronomers has already produced exceedingly useful data for Kapteyn's Selected Areas and the younger generation in the United States, Sweden, Germany and Russia is now making every effort to clear up the color situation for the whole of the Milky Way.

Is the Haze Patchy?

How regular or irregular is the distribution of the interstellar dust in the general haze? Is it smooth or does the superposition of many single dust clouds produce the total effect that we observe? At present it is impossible to give a positive answer to these questions. There is apparently no region along the galactic circle where the view is perfectly clear. In a few places some galaxies shine through the haze in the galactic belt, but even there the number of faint galaxies is far below par and a total absorption of several magnitudes is indicated.

Because of the irregularities in the true distribution of the faint external galaxies (they are inclined to come in bunches too!) estimates of total absorptions at a given point from galaxy data may well be off by as much as half a magnitude. In spite of such uncertainties the observed deficiencies in the numbers of faint galaxies can teach us much about the extent of some of the largest single clouds. The large dark nebulae in Orion and Taurus, Cepheus, and

Ophiuchus are not only star-poor regions, but they are also deficient in faint galaxies.

We should not underestimate the total effect of the isolated dark nebulae. Only the nearest of those nebulae will be discovered by an inspection of Milky Way photographs. The Southern Coalsack is conspicuous to us because it is probably well within five hundred light years and covers a large angular field. But we should realize that it would hardly have been detected if it had been ten times as far away at five thousand light years. Not only would it then cover only one per cent of its present area, but it would further lack contrast because of the many foreground stars. Greenstein has computed that the known dark nebulae alone may account for thirty percent of the total haze for distances up to three thousand light years.

Do we observe any reddening effects in regions along the Milky Way where there is no evidence at all for an overlying dark nebula? We can make the test for a region in Monoceros, directly north of Sirius, which is surprisingly free of dark lanes and other evidence of local obscurations. An extensive spectrum—color survey at Harvard shows that the reddening is small though not totally absent. Right at the galactic circle the observed reddening indicates a total dimming of the order of half a magnitude at a distance of five thousand light years; but as little as two degrees north of the plane no reddening effects were observed. As far as we can tell today there is probably something of a continuous haze, but it seems as though the isolated dark dust and gas clouds are responsible for at least half the observed absorption and scattering.

There was once a lady on a visitor's night at the Lick Observatory who expressed a desire to see "infinite space." The astronomer in charge of the 36-inch refractor solemnly

turned the telescope to a starfield with very few stars and suggested that she look to her heart's content in between the stars. That happened some twenty years ago. Twenty years is a long time and if the lady really wishes to be certain that she has gazed upon infinity she had better make a second trip to the top of Mount Hamilton. For during the twenty years the cosmic haze has been closing in on us and we now realise that, without special care, the inquiring woman may really have looked at some obscured field.

9

MEN AT WORK

MILKY WAY RESEARCH IS COMING OF AGE. THE STAR gauges of the Herschels marked its beginning, Kapteyn and his contemporaries saw it through the difficult formative period and the present generation of astronomers must launch it on a worthwhile career. The future looks bright, for not only have we telescopes and other tools of research that far exceed what seemed in prospect forty years ago, but we start off with a substantial endowment of basic material on spectra, magnitudes, motions and other characteristics of the stars in the Milky Way. The two-fold job ahead of us is perfectly straight-forward. Through intelligent use of the new tools and techniques we should be able to add rapidly to the growing body of basic data. As we put our base camp in order we shall find more and more opportunities for treks into the unexplored researches of our vast galaxy.

JOBS FOR THE OBSERVER

Our knowledge of galactic structure depends directly on the quality and quantity of the basic data that are at hand. We are constantly clamouring for more and more accurate

information on the magnitudes, spectra, colors and motions of the stars.

The work on trigonometric parallaxes is progressing quite satisfactorily. Most of the giant stars are too distant for accurate direct parallax work, but there remains much to be done for the intrinsically faint stars. For the study of stellar motions, as well as for further studies of the luminosity function, the measurement of the parallaxes of faint stars with large proper motions remains of primary importance.

In the field of stellar proper motions there is also little reason for complaint. Since the completion of Boss's General Catalogue the most valuable type of research has been the measurement of the proper motions of all stars to the ninth and tenth magnitude in successive zones of declination. The detection of faint stars of large proper motion is so far along that many years of research are already laid out for those who wish to determine the trigonometric parallaxes, spectral types, and radial velocities of such stars. An urgent project is the measurement of very accurate proper motions for stars between the thirteenth and eighteenth magnitude. That problem is, however, exceedingly difficult since, in addition to small accidental errors, we should request a virtual absence of systematic errors of all kinds. The difficulty may be solved by the use of faint extragalactic nebulae as the ideal reference system. Their proper motions are extremely small—of the order of one hundred thousandth of a second of arc in the course of a year. They appear as stellar images in sufficiently large numbers on plates taken with the Schmidt and Ross type cameras. If we can succeed in measuring stellar positions with reference to these faint nebulae we should be able to derive proper motions free from systematic errors.

Our knowledge of stellar radial velocities is complete for the naked-eye stars, reasonably complete for the stars

between the sixth and eighth magnitudes, and very incomplete for the fainter stars. Our knowledge of the mechanics of our galactic system depends more on the volume of our information on radial velocities than on anything else. Radial velocities of distant *B* and *A* stars, Cepheids and clusters have yielded direct proofs for the theory of galactic rotation and the best general information about interstellar absorption. It is useless to have excellent proper motion data unless one has also radial velocities.

We need radial velocities for the faintest stars within reach of our equipment. We are however willing to accept for faint stars somewhat lower accuracy than that which is now attainable for the brighter stars, if, by so accepting, we can penetrate into the more remote parts of our galaxy. The "slit" spectrographs which work on one star at a time will probably not be able to supply enough radial velocities to meet the demands. The increasing use of the objective prism technique should make it possible to reach great numbers of stars.

Spectral types of faint stars have proved so valuable for galactic research that astronomers are always asking for more. Within a few years we should know the spectra of stars to the eleventh magnitude for most of the Milky Way. That will only be the beginning, for soon we shall wish to obtain individual spectral types for stars of the sixteenth magnitude. A knowledge of spectral types is about as important for the study of structural details as is a knowledge of radial velocities for the study of the mechanics of our galactic system.

Spectral classification serves a double purpose. First, from the spectral class of a star we can determine the approximate value of the star's intrinsic brightness—its absolute magnitude. If you were to discover a faint *A* star along the Milky Way the chances are that you would have

found a star that is at least ten times as bright as our sun. Second, from the spectral class of the star, as judged from the lines in its spectrum, the true color of the star can be predicted, and by comparison with its observed color the amount of reddening that the light of that star has undergone in its passage through space can be found.

The recent advances in telescopic construction promise well for the future of spectral classification. Several of the new large Schmidt cameras are being adapted for classification work and most large reflectors are now provided with fast slitless spectroscopes. We may not yet be able to get sixteenth magnitude stellar spectra good enough for classification purposes, but we can reach the fourteenth magnitude without too much effort.

The spectroscopic measurement of absolute magnitudes of faint stars is a refinement of the adopted scheme of spectral classification. Accurate spectroscopic absolute magnitudes have been determined for naked-eye stars at the Mount Wilson, Victoria, Harvard, and Yerkes Observatories, but the work on the fainter stars has only just begun. Successful efforts have been made by Lindblad, Schalén and other Swedish astronomers, but rough estimates of absolute magnitude are still lacking for the majority of the stars of known spectral class.

A general availability of standard sequences of magnitudes in different colors has always been so obviously a necessity for galactic research that it may come as a surprise that dependable sequences are by no means as numerous as they should be. The photographic sequences in the northern sky are excellent at least to the eighteenth magnitude. Seares and van Rhijn are largely responsible for the accurate sequences in the northern selected areas, but south of declination $-15°$ no reliable sequences are yet available for stars fainter than the fourteenth magnitude. The need

for such standards for faint stars in southern selected areas is urgent. The region of the galactic center and the critical Carina section of the Milky Way fall both in the part of the sky where reliable sequences for faint stars are still lacking.

It is essential for color work that we should have, in addition to good photographic sequences, equally reliable standard sequences for photo-visual or photo-red work. With the rapid increase in the speed of red-sensitive plates during recent years the photo-red sequences have become particularly important. Good red sequences are available at the North Pole and for some other special regions, but the basic work is by no means completed in this department.

There are roughly one million stars brighter than the twelfth photographic magnitude, which is the practical limit for most spectral classification and color jobs, and it is well within the realm of possibilities to determine spectral types, magnitudes and colors for all stars to that limit. But even though it might become a fairly simple matter to measure spectral types and colors down to the fifteenth magnitude, we could not—and presumably *should* not,—look forward to the measurement of these attributes for all fourteen million stars between the twelfth and fifteenth magnitudes. It should suffice to do so for only a relatively small fraction of all these stars.

How are we to select the regions that deserve special attention? It is here that general starcounts are important and we may now turn our attention to them.

A starcounting project is basically a high-speed magnitude job. In the measurement of stellar magnitudes we are interested in two things, first, the photographic magnitude of a star; second, some form of identification that renders it possible for anyone to locate at any time the particular

star to which that magnitude estimate refers. In starcounts we are not interested in the exact location and magnitude of a given star. We only wish to know how many stars there are between set magnitude limits for a particular area of the sky. If a standard sequence is once established in such an area we can make star counts from photographs in the surrounding region without it being necessary to identify individual stars. The counts can either be made directly by an astronomer peering through a low-power microscope, or we can use a mechanical means such as is provided by the automatic starcounting machine developed by McCuskey and Scott in Cleveland.

We have already described in a previous chapter how a group of astronomers associated in part with Harvard has undertaken to count stars along the entire Milky Way down to the fifteenth magnitude. This project is rapidly approaching completion, but what is to be done about the stars between fifteenth and eighteenth magnitude and the uncounted millions beyond that limit? Perhaps the mechanical starcounter may come in handy, for it would certainly be a waste of time to tackle the job humanly with the aid of a binocular microscope. On the basis of the fifteenth magnitude survey it will probably be possible to select certain small representative areas for which the starcounts should, with the aid of Schmidt cameras and large reflectors, be extended to the faintest limit within reach of modern equipment.

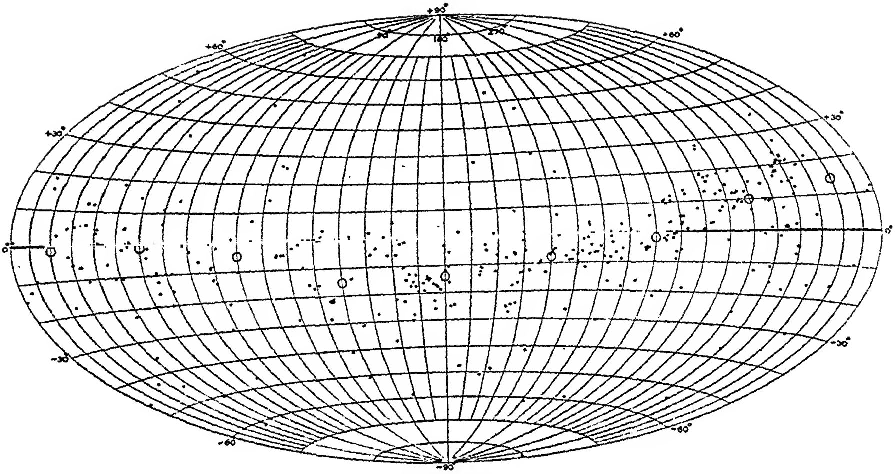
Parallaxes, motions, spectra, magnitudes, . . . and we could continue by discussing the need of more detailed observations of variable stars, the hope for the discovery of more distant clusters and special peculiar objects, and the need for full information about the distribution of galaxies along the galactic belt. Much work remains to be done in all these fields of research.

Astronomy is a science in which numbers count. One single simple observation is generally of little value, a hundred or a thousand observations of a similar nature may mean a contribution of some significance, while the same type of observation repeated a million times may mean one of the greatest contributions to scientific progress.

Where are we now in the general scheme of progress? The year 1901 marked the middle of the period of experimentation with new methods and new techniques. By 1921 the technical difficulties had been largely surmounted and the first attack was well under way. But the objective was limited; for the fainter stars, effort was concentrated largely in Kapteyn's selected areas and it was only for the brighter stars that attempts were made to cover the whole sky. 1941 finds us right in the midst of the broad attack to cover the whole Milky Way. It is a dangerous business to predict where we may be by 1961. If astronomy is allowed to progress freely we shall probably have witnessed before that day the completion of most of the projects that we have discussed so far in this chapter. It may seem like a rash program to many of our professional colleagues—but we should be ashamed of ourselves if we have not succeeded by that time in demonstrating the arrangement and mechanism of that part of our galaxy that is within five thousand, or even ten thousand light years from the sun.

Local Structure

There are many indications of local structure in the distribution of the brighter stars. You do not have to go beyond the naked-eye stars to find the first traces. A hundred years ago, on his expedition to the Cape of Good Hope, Sir John Herschel noticed that the brightest stars in the sky lie along a circle that is inclined twenty degrees to the plane of the Milky Way. Herschel's remark was nearly forgotten,



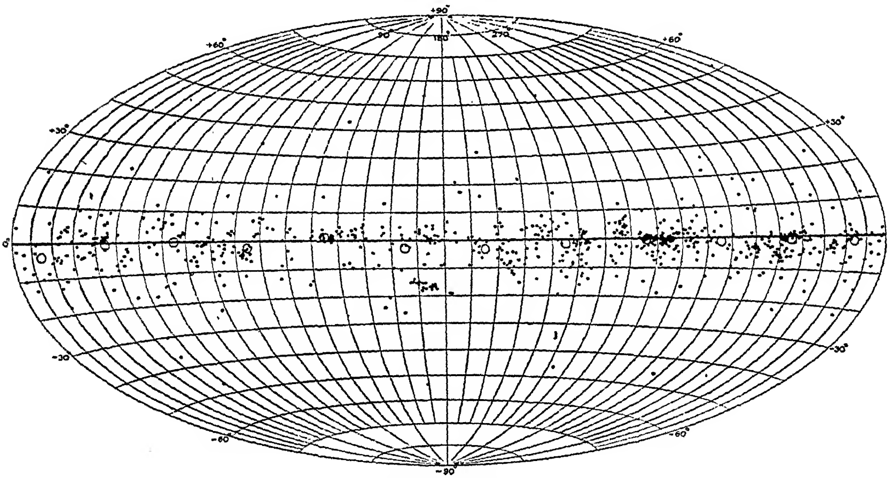


Fig. 83.—Gould's Belt among the B stars.

The distribution of the B stars brighter than the fifth magnitude shows the presence of Gould's Belt. The fainter B stars fall mostly close to the Milky Way.

but in 1879, Gould, an American astronomer then the director of the observatory at Cordoba in the Argentine, drew further attention to the phenomenon. He wrote in the introduction to the star catalogue known as the "Uranometria Argentina":

"It appears as a stream of especially conspicuous stars, which, beginning with Orion, includes the brightest in Canis Major, Columba, Puppis, Carina, Crux, Centaurus, Lupus, and the head of Scorpius. In the northern hemisphere its course is less distinctly marked, and it is especially indistinct in Ophiuchus and Hercules; but its general direction is indicated by the brightest stars in Taurus, Perseus, Cassiopeia, Cepheus, Cygnus, and Lyra."

and further on the same page:

"Thus I cannot avoid the conviction that our system forms part of a small cluster, distinct from the vast organization of that which forms the Milky Way, and of a flattened and somewhat bifid form. This cluster may perhaps be comparable with the Pleiades, since by a crude estimate it would seem to consist of less than 500 stars."

Figure 83 shows how pronounced the effect of "Gould's Belt" is on the distribution over the sky of the *B* stars visible to the naked eye. At the center of the upper diagram the *B* stars are most frequent about fifteen degrees south of the central line of the Milky Way, while to the right they are equally far above it. The lower diagram of the same figure shows that the telescopic *B* stars behave quite differently. Apparently they prefer the central line of our Milky Way.

Gould's Belt is most pronounced among the brighter *B* stars, but it is not wholly confined to this type of star. The *A* stars, even those below naked-eye visibility, show very much the same trend and the nearby dark nebulae clearly prefer Gould's Belt.

Does Gould's Belt necessarily point to the existence of a local system? Something like it ought to be observed if the sun would happen to be located in a relatively small sub-system of the galaxy, for which the plane of symmetry were tilted with respect to the general galactic circle. But what we observe may be explained in other ways.

A close examination of the upper diagram in Figure 83, shows that the evidence for Gould's belt depends mostly upon two groups of bright *B* stars. One group in Orion lies south of the galactic plane, the other group in Centaurus lies north of that plane. If these two groups are removed, the rest of the *B* stars lie generally close to the Milky Way. Instead of postulating a single unit local system we need only assume the existence of some special condensations.

If our sun is involved in a local condensation of stars, we should expect that the star density ought to drop as we move away from the sun. Do we observe anything of the sort? The absolute magnitudes of the *B*0 to *B*5 giants are so bright that these stars offer an excellent opportunity for a critical test. All *B*0 to *B*5 stars within three thousand light years of our sun have already been catalogued. van Rhijn of Groningen has counted how many of these stars are found for successive intervals of apparent magnitude directly in the band of the Milky Way. Since the average amount of interstellar absorption over the first four thousand light years is probably not more than three or four tenths of a magnitude for each thousand light years, we can compute from van Rhijn's counts if, and how rapidly, the giant *B*0 to *B*5 stars thin out.

Figure 84 shows what comes from these calculations; the *B*0 to *B*5 stars are apparently thinning out very rapidly. It would seem very unlikely that this trend could be reversed as more data on absorption become available.

We have given for comparison the density curve for all spectral types combined, also computed by van Rhijn. The difference in the rate of decrease for the two curves is very significant. It shows that the percentage of *B* stars among all types combined decreases by a factor of at least

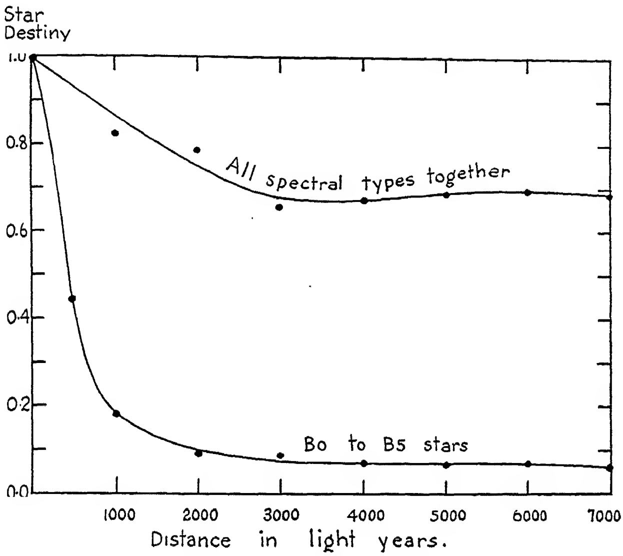


Fig. 84.—The local condensation of B stars.

The density curve for the B stars compared to that for all spectral classes combined according to van Rhijn.

one-fifth as we move out from the sun to a region five thousand light years distant.

We have learned, however, to be suspicious of "averages" for the entire Milky Way and we ask now what we find if we examine separate sections of the Milky Way.

Suppose that we should find a thinning out in all directions. This would imply that we are located in a condensa-

tion and near the center. If the star density would remain more or less constant everywhere within a radius of three thousand light years of our sun we would believe ourselves in a region free from pronounced structure. We should, however, consider some further possibilities. Imagine that we were in a spiral arm. The density would then be more or less constant along the direction of the arm, but it should drop appreciably for directions in the galactic plane at right angles to the supposed spiral arm. Again, we might imagine our sun to be in an empty region between two spiral arms. Instead of a gradual thinning out we would expect an increase in star density with distance from the sun, at least for some directions.

At the present time astronomers are by no means agreed whether or not the stars thin out as we move away from the sun in various directions in the galactic plane. Our lack of information concerning the amounts of interstellar absorption is the chief stumbling block. If we simply neglect the absorption in the analysis of observed star numbers, stars of all types seem to thin out in all directions. Interstellar absorption and scattering is, however, present almost everywhere along the Milky Way and we can rest assured that we are not justified in leaving out entirely absorption effects.

It seems fairly well established that the star density drops for some directions in the Milky Way and probably only fluctuates for some other sections. A gradual thinning out is fairly well established for the sections from Monoceros to Taurus, which is known as the anti-center region, since it is opposite the central star clouds in Sagittarius.

There is little indication of any thinning out over the first three to five thousand light years in the directions of Cygnus, or Carina, both of which are at right angles to the direction of Sagittarius. The stars in Carina are so closely packed

Fig. 85.—A region near the galactic center.

From a photograph by Duncan with the 18-inch Schmidt camera at Mount Palomar.

that we find at a distance of five thousand light years a star density well in excess of that near the sun.

The region of the central star clouds in Sagittarius is in many ways the most important of all. If the star density were first to decrease with distance from the sun and then, at a much larger distance, tend to increase, we would construe this as evidence that the sun is in one of the spiral arms. If, on the other hand, the star density would be found to increase steadily, Gould's belt and its associated effects would then seem to be rather a minor fluctuation.

We hardly need to explain why the analysis for the central regions in Sagittarius is still incomplete. The central star clouds are veiled in obscuration and our available data on colors are by no means sufficient to unravel all mysteries for this part of the Milky Way. The nature of the interstellar reddening seemed so complex that astronomers had almost given up hope of being able to find the star density for the direction of the Sagittarius clouds. But with the gradual accumulation of absorption data from colors of distant stars we begin to gain more confidence in our battle against interstellar obscuration. With another five or ten years of carefully planned research we may be able to clear up the existing uncertainties.

The Outlines of Our Galaxy

Our Milky Way is so complex and irregular that we should always guard against generalizations from insufficient data. There is, however, a danger that we may fail to see the woods because of the trees. While it is important that we should ferret out details of structure, we should always remember that our final aim is the study of the general outlines of our galaxy.

We are convinced that directly in the band of the Milky Way we cannot at present penetrate far enough to unravel

the detailed structure of the nearer parts of the galaxy. The relative uncertainties increase of course as we pass to the more distant parts. Uncertainties about the absorption effects, coupled with a suspicion of variations between the spectral make-up in various parts of the galaxy, lead us to explore the less densely populated parts of the Milky Way system.

If we look ten to twenty degrees from the central line of the Milky Way, we find regions far less spectacular than those shown on the familiar Milky Way photographs. The stellar distribution is more regular, though there are still many stars per square degree. Long exposure photographs frequently show small diffuse objects that are faint external galaxies far beyond our own system. The presence of these galaxies shows that the total absorption for that particular direction is not immeasurably large, though it may be as high as two or three magnitudes. The total number of galaxies on a photograph is a fairly accurate measure of the total absorption. The estimated total absorption can be corroborated by the colors of the distant stars in the region. When the total absorption is known with some accuracy we can proceed to analyze the density distribution of the stars for each spectral class separately and collectively. Since the total absorptions are generally small, the analyses for variations in the average star density per unit volume reach to fairly large distances.

It is very difficult to go beyond five thousand light years in a low-latitude field, but in intermediate latitudes ($\pm 10°$ to $\pm 20°$) we can frequently compute the star densities for distances up to twenty thousand light years. It is important to realize that we may in these latitudes reach to great distances from the sun without going far from the galactic plane. Figure 86 shows that for galactic latitude ten degrees at a distance of six thousand light years we are

only a little more than one thousand light years above or below the plane. It becomes then of interest to compare the star density at a distance of one thousand light years above or below the galactic plane for our field in intermediate latitudes with the star density at a thousand light years in the direction of either galactic pole.

By combining the results of the analyses for many fields in intermediate latitudes we can find at what heights above or below the galactic plane a star population of one half,

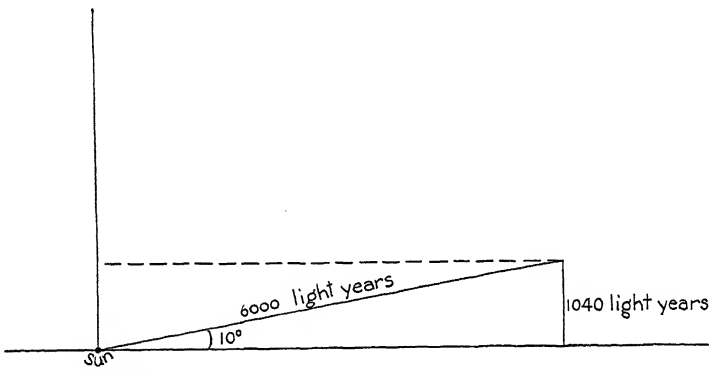


Fig. 86.—Height above the galactic plane.

one fifth or one tenth of that near the sun is reached. If a large number of fields is so investigated we may hope to find the shapes of the "surfaces of equal star density" for the thinner parts of our galactic system.

Oort has investigated the stellar distribution in intermediate latitudes along the lines that we have just indicated. The curves for star densities less than one tenth that near the sun are smooth elongated figures. But the Milky Way system is apparently thicker near its center than in the outlying regions. The surprising part of Oort's results is the peculiar behavior of the star density in the immediate vicinity of the sun. Oort's curves of equal star density

indicate that the sun is located in a regior of sub-normal density. It looks as though we are in the hole of a doughnut! This result is contrary to what we had found from the study of stellar distribution in the galactic plane where we found a decrease in the star density for the direction away from the center.

We are sorry, but we simply do not know which of the two results is right. The low-latitude analysis is uncertain because of difficulties with interstellar absorption and possible changes in the luminosity function. Oort's analysis suffers from incomplete data on stellar colors and the distribution of galaxies. The authors feel, however, that they do not owe an apology to their readers. The title of this chapter is "Men at Work" and we can assure you that astronomers are making every effort to clear up the existing discrepancies.

In the study of the outlines of our galaxy, variable stars figure very prominently. Shapley's studies on variable stars in galactic clouds and globular clusters twenty-five years ago, gave the first definite proof for the eccentric position of the sun in the galaxy. Variable stars are now contributing effectively to the further exploration of the stellar distribution near the galactic nucleus and are probably the best "tracers" for the emptiest outer regions of our galaxy, far from the galactic plane.

The frequency of faint cluster variables in high galactic latitudes, as found by Shapley and his associates, is surprisingly high. One quarter of all known cluster variables not in globular clusters are between galactic latitudes $\pm 30°$ and $\pm 90°$. Shapley's analysis shows that these variables thin out gradually as we extend our explorations to larger distances from the galactic plane. Apparently the cluster variables are part of a tenuous extended aura of our galaxy. According to Shapley the outer surfaces of equal star density

Fig. 87.—A transparent region south of the galactic center.
Harvard Observatory photograph.

are almost spherical in space. Shapley's thin globular "corona" of stars is probably one of the characteristic features of galactic structure.

The discovery and study at Harvard of faint cluster variables in two fields fifteen to twenty degrees from the galactic circle directly south of the Sagittarius cloud has led to interesting results. Faint galaxies appear in abun-

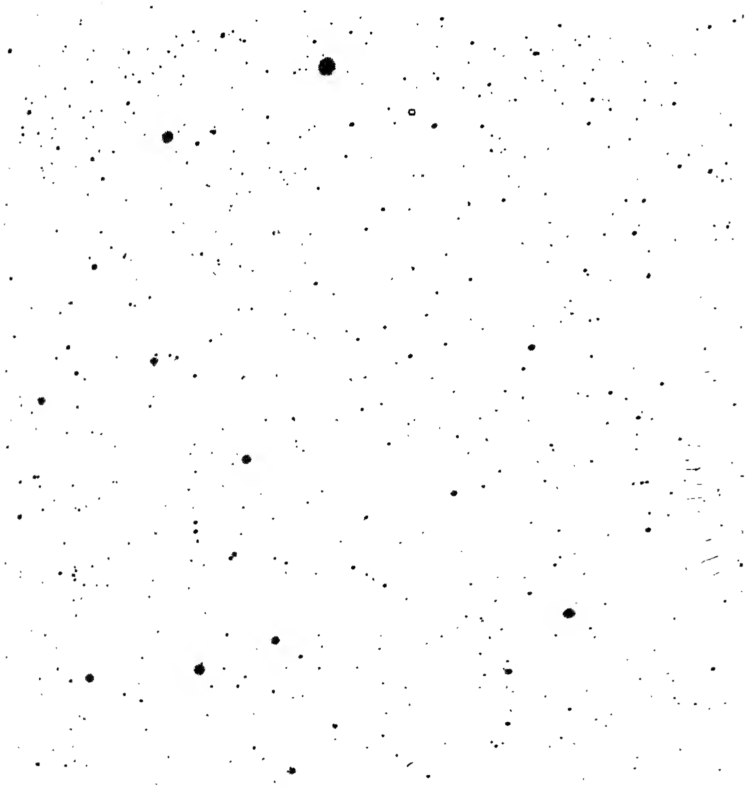


Fig. 88.—Faint galaxies in low latitudes.

This photograph shows a small section of the area marked in Figure 87. Two faint galaxies are discernible. Harvard Observatory photograph.

dance in both fields and we may therefore compute the total amounts of the interstellar absorption. These total absorptions are in each case of the order of half a magnitude. The observed distribution of the cluster variables in apparent magnitude can then be corrected for absorption effects. The results show an increase in the number of the variables at a distance of thirty thousand light years.

The discovery and measurement of cluster variables is a slow and cumbersome process, but judging from the results that have already been obtained these kinds of studies are yielding highly significant data on the structure of our Milky Way system.

10

EXPLORATIONS IN SPACE

The Grand View

*H*ave you ever stopped to think how much easier the job of the Milky Way investigator would have been if our sun had happened to be some five or ten thousand light years above or below the galactic plane, instead of being almost exactly in it? We are located in just about the worst possible place for observation. Not only are we at the outskirts of our galaxy, some thirty thousand light years from its center, but we are also in such a dusty region that we cannot see far in any direction in the galactic plane. It is as though we were attempting, on a foggy day, to study the plan of a large city from the roof of a not-too-high building somewhere in the suburbs.

It may almost seem out of place to give the cheerful title "The Grand View" to a section that starts off in such a gloomy fashion. We should not be over-optimistic, but at the same time let us keep our cheerful title and try to present, as far as this is now possible, a picture of how our Milky Way system would look to an outside observer. Not long ago we suggested to one of our graduate students at Harvard, Albert G. Mowbray (who was visiting for a year

from the Lick Observatory) that he gather some numerical data on the probable appearance of our Milky Way system as viewed from distant points. Mowbray's report has appeared in the December 1940 number of the monthly magazine "Popular Astronomy" and we shall make use of his data in our discussion.

Since we have fairly complete information as to the structure of the galactic system within three thousand light years of our sun, we should first ask how our neighborhood would appear to a distant observer. Suppose that we could send an observer with some telescopes off into space in a direction at right angles to the plane of the Milky Way (that is toward one of the galactic poles). We would suggest that he stop three times on his way toward infinity, at distances one hundred thousand, one million, and ten million light years. On each occasion he should pick out our Milky Way system among the many galaxies, take some photographs of the region around the sun, and return the plates by celestial express before proceeding to the next stop. We shall suppose that his equipment consists of an 8-inch Ross camera and a duplicate of the 200-inch reflector that is being erected at Mount Palomar in California.

Our observer would have no great difficulty in locating our galactic system from a distance of one hundred thousand light years. It would appear as a faint roundish bright patch fifty degrees across. The total luminosity of our Milky Way system is probably equivalent to an absolute magnitude of −20, so that the total apparent magnitude of our system as viewed from a distance of one hundred thousand light years would be of the order of −2.5. Under good conditions we receive about that much light from Venus. Our Milky Way could probably be traced but it is very doubtful that the outlying portions of our galaxy would be bright enough to be visible to the unaided eye.

What would be the appearance of the part of our galactic system within a few thousand light years from the sun? Since the sun is roughly thirty thousand light years from the center of the galaxy, our observer would look for the sun fifteen to twenty degrees from the center. The prospects would not seem very encouraging. According to Mowbray's calculations (which confirm in a general way some earlier work by Seares) the surface brightness of the region around the sun would amount only to the equivalent of one sixth magnitude star per square degree. That is too faint to be above the limit of visibility. We might mention for comparison that Pannekoek's photographic measurement of surface brightness along the Milky Way shows that the medium bright sections, such as those in Monoceros, Perseus, or Cassiopeia, send us the equivalent of four to five sixth magnitude stars per square degree.

From a distance of one hundred thousand light years our observer would certainly not find it an easy task to locate the sun itself. It might just appear on a long exposure with the 200-inch reflector, but the 8-inch camera would be useless. At a distance of one hundred thousand light years our sun would be a very faint star of the twenty-third magnitude. The region around the sun would probably be most clearly marked by a group of twelfth to fifteenth magnitude stars. Most of these would prove to be luminous *O* and *B* giants, but later type giants, some of them Cephied variables, would also be present. The plates taken with the 8-inch camera would probably show some tenth magnitude stars, a few bright unresolved clusters and perhaps a few patches of nebulosity. An occasional eleventh magnitude nova would serve to break the monotony.

Would the fainter stars be so close together that they would not be resolved on our photographs even though they might be bright enough to fall within the reach of the

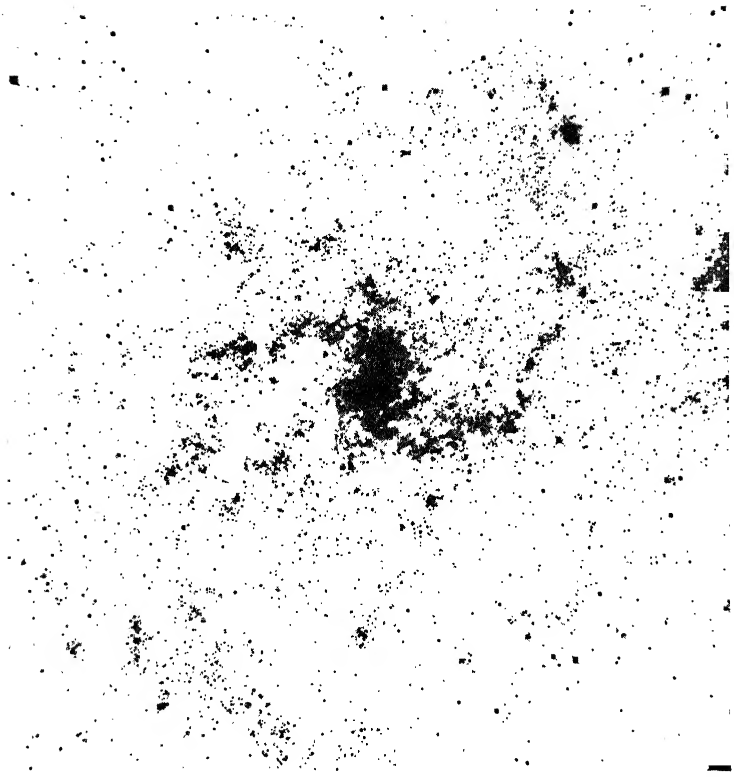


Fig. 89.—The Spiral Nebula Messier 33.
From a photograph taken with the 60 inch telescope at Mount Wilson.

telescopes? Mowbray's calculations show that we live in such an empty section of the Milky Way that all the sun's neighbors bright enough to be recorded would be photographed as separate dots. If our observer would, however, set his telescope on the denser central region of our galactic system the stellar images might coalesce. Our galaxy would probably appear very much as some of the nearer spirals appear to us. The outer parts could be resolved but the

central region would only be recorded as a bright nebulous patch.

At one million light years the 8-inch camera would readily record our galaxy as a diffuse patch with a diameter of five degrees, but now even the bright *O* and *B* stars near the sun would be too faint to register. The 200-inch would take over where the 8-inch left off and the stars, clusters and nebulae that would register on the plates taken with the 8-inch camera at one hundred thousand light years would now only come through on the plates taken with the large reflector. The whole galaxy would appear a little brighter than the Andromeda nebula does to us, but it would not be very conspicuous.

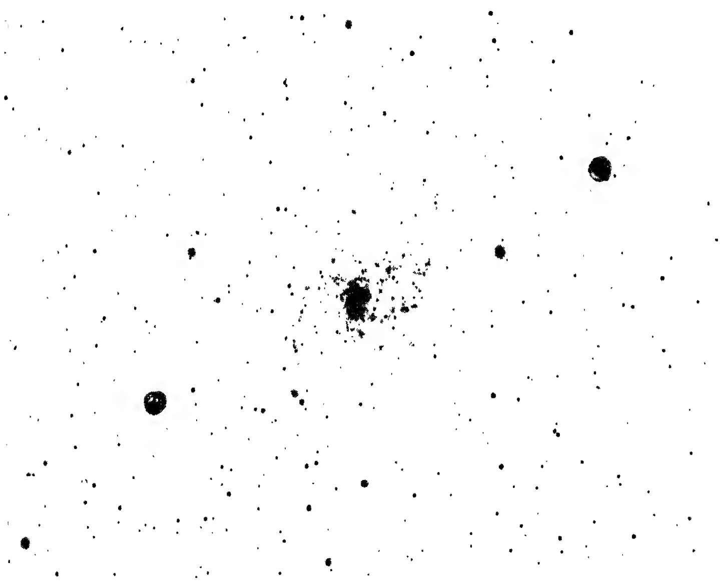


Fig. 90.—A small scale photograph of Messier 33.

The white dots mark the positions in Messier 33 where the surface brightness equals that of our galaxy for the vicinity of the sun. Harvard Observatory photograph.

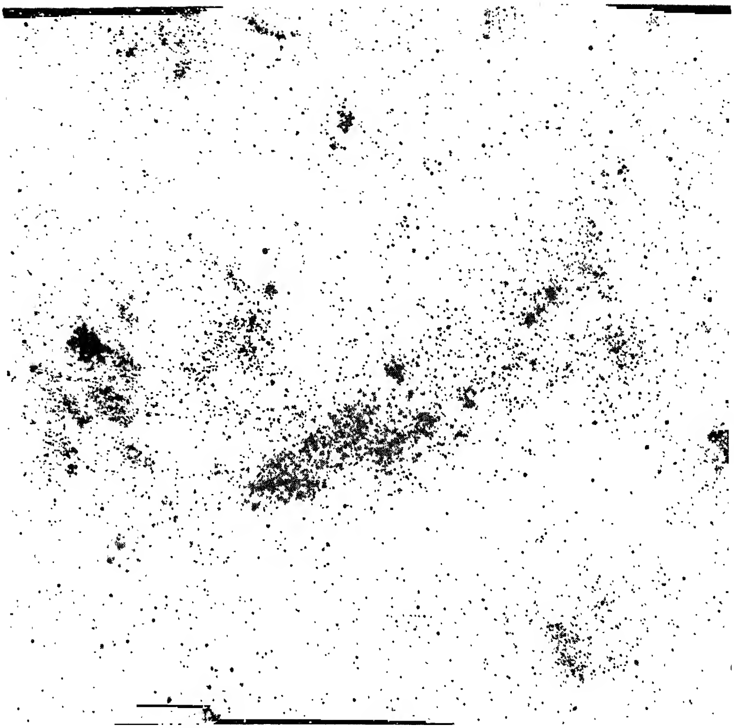


Fig. 91.—The Large Magellanic Cloud.
Harvard Observatory photograph.

At ten million light years our galaxy would have shrunk to a hazy patch about as big as the moon (half a degree in diameter) but with a total brightness corresponding to a seventh magnitude star. It would come out nicely on a ten-minute plate with the 8-inch camera, but even the 200-inch would reveal little detail. The brightest supergiants would register as twentieth-magnitude stars.

In Figures 89 to 93 are shown typical photographs of some of the nearer galaxies. The Large Magellanic Cloud is very nearly at a distance of one hundred thousand light

years from the sun. The spirals Messier 33 and the Andromeda nebula are somewhat closer to our sun than one million light years, but their photographs show what is the general appearance of a large galaxy from a distance of the order of one million light years.

The dots in Figure 90 mark the places where the surface brightness in Messier 33 equals that computed for the part of our galaxy in the vicinity of the sun. We are in a truly inconspicuous part of our Milky Way system!

Figure 92 shows a close-up of a not-too-dense section in the Large Magellanic Cloud. The photographs of the region

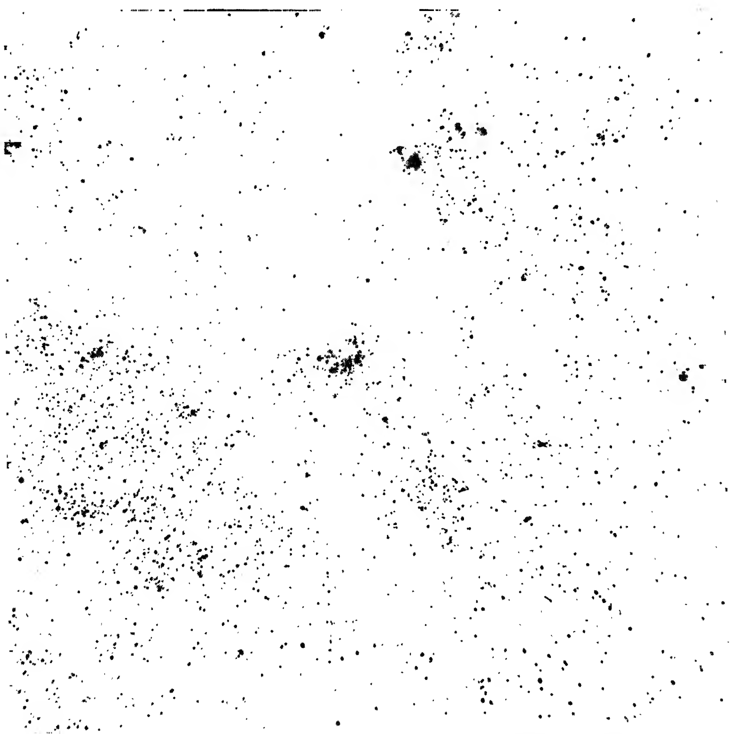


Fig. 92.—A section of the Large Magellanic Cloud.

around the sun taken from the distance of one hundred thousand light years with the 8-inch camera would probably look very much like Figure 92.

Do We Fit In?

We have wandered far on our intergalactic journey, and it is about time that we get back to earth. How does our galaxy fit in among other galaxies?

We possess at present fairly reliable estimates of the total mass and dimensions of our Milky Way system. The system is highly flattened with a diameter of the order of one hundred thousand light years. The sun is located at a distance of thirty thousand light years from the galactic center. The mass of the system is probably as high as two hundred billion (2×10^{11}) solar masses. There may be spiral structure in the system, but the evidence on that point is none too clear. The system as a whole rotates around the distant center; this rotation being such as would appear if at least half the mass were in the central region. The sun is probably in one of the thinner outlying portions of the galaxy, where the surface brightness for an outside observer would hardly exceed one star of sixth magnitude per square degree. And finally, our system is so full of dust that for the neighborhood of the sun we estimate that half the total material density is in the form of interstellar dust and gas.

Our system has probably much in common with the Great Spiral in Andromeda. The total mass of the Andromeda nebula is estimated as high as one billion solar masses, and its outer dimensions are somewhat, though not appreciably, smaller than those of our galaxy. The measured surface brightness for a region at sixteen thousand light years distance from the center of the Andromeda nebula is just about equal to that computed by Mowbray for the regions around the sun.

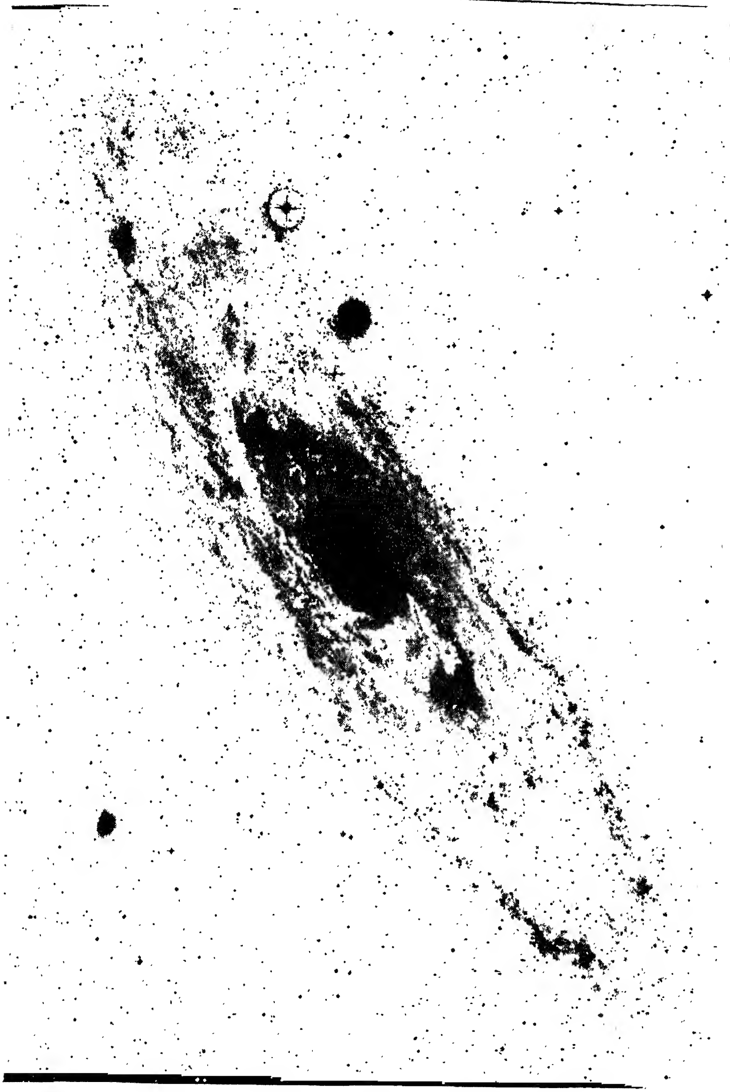


Fig. 93.—The Great Spiral in Andromeda.
From a photograph taken at Lick Observatory.

So far all is well with the comparison, but when we examine the rotation of the Andromeda nebula we find a different scheme from that of our galaxy. According to Babcock's observations at Lick Observatory, the outer parts of the Andromeda nebula rotate like a solid wheel. This would seem to indicate that much of the mass, but a surprising small fraction of the total light, is found in the outer regions of the Andromeda nebula. We are uncertain about many features of galactic structure, but the observations on the rotation of our galaxy show that the stars in the region within ten thousand light years of the sun do not move like a solid wheel around the galactic center. It seems well established that in our system the rate of rotation decreases as we go further from the center.

As far as its rotational properties go, our own galaxy would seem to have more in common with the spiral Messier 33 in Triangulum. Mayall and Aller have found from observations on the radial velocities in various points in this spiral nebula that the inner region, with a diameter of the order of six thousand light years, rotates as a solid disc, but that the rate of rotation drops rapidly as we pass further from the center. The rotational speeds in Messier 33 drop so rapidly in the outer regions that it would seem as though practically all the mass were in the central star cloud.

Messier 33 is apparently much like a small scale model of our galaxy. Its total mass is probably not higher than one billion (10^9) solar masses, which would make it only one one-hundredth as heavy as our galaxy. A surface brightness equal to that near our sun is measured at a distance of five thousand, rather than thirty thousand light years, from its center.

Ten years ago our own galaxy seemed exceptional in almost every way. It was apparently brighter, bigger and

heavier than any of its fellow galaxies. As research in galaxies progressed our home galaxy began to fall more and more in line. The brighter spirals were found to extend by a factor of two or three beyond their originally estimated diameters. The earlier estimates of their masses were revised upward as observations on the outer regions became available. Further, when it was found that the light of distant stars in our galaxy was dimmed by interstellar absorption, it became evident that the size of our galaxy had been overestimated.

Modern Milky Way research shows that our galactic system is probably not unlike many other galaxies. It is apparently a giant system, but in spite of its large size and mass it has some pretty close rivals in the universe of galaxies. We like to think that we are part of a good-sized stellar system, but we should have been rather embarrassed —and suspicious too!—if we had found ourselves in the biggest of all.

11

HOW OLD IS THE MILKY WAY?

OUR MILKY WAY IS CONSTANTLY CHANGING. THE changes are so slow that we have to use excellent telescopic and measuring equipment for their detection. It may take ten, twenty or a hundred years of patient observing before certain changes can be verified. While these may seem very long intervals to us, they are mere passing moments in the development of the cosmos. Instead of using the year as a yardstick, we shall introduce its cosmic equivalent, the time during which our sun makes one complete revolution of our galaxy. A cosmic year represents two hundred million of our more familiar solar years.

What are the changes that take place if we think in terms of cosmic years? The stars of the galactic system are continually being reshuffled. As small a difference in speed as one mile per second will serve in the course of one million years to separate two stars by a distance of five light years. Groups of stars may be formed, others will be dissipated and profound changes may take place in the spiral appearance of a galaxy.

In addition to these purely mechanical changes other forces are at work in the galaxy. The stars are always

pouring out radiative energy without any apparent return of radiation. We wonder how long the stars can keep up their futile efforts to warm up the great outdoors of empty space. Are the stars gradually running down because of the continuous loss of energy and, if so, what changes occur in the course of one or several cosmic years?

Large Scale Changes

The fact that the individual stars are in rapid motion does not by itself imply that the system as a whole is changing appreciably. Let us consider a spiral system such as Messier 33. It may be that as one star moves out of one of the knots of the spiral arm into a relatively empty space between the arms, another star moves in. The configurations in a stellar system may be relatively permanent while the component stars are constantly moving from one part to another. The red and white blood corpuscles are always leading a merry chase through our veins and arteries, but the amount of blood in a given vein does not as a result vary appreciably.

If the distribution of positions and motions in a galaxy is such that no large scale changes take place, we speak of the stellar system as in "dynamical equilibrium." Such a state of equilibrium is, however, not going to remain unchanged for ever and ever. It might last for a hundred of our cosmic years, but the chances are that it could not survive unaltered for as many as ten thousand cosmic years. For intervals longer than ten billion solar years the effects of chance encounters with passing single stars begin to be appreciable and the dynamical equilibrium may be upset in the course of a hundred or a thousand billion solar years.

Unfortunately we know as yet too little about the details of the structure and motions in our Milky Way system to predict probable changes with any degree of reliability.

The situation, however, is not quite hopeless. In another twenty five years we ought to have rather complete information on the numbers and velocities for the stars within ten thousand light years of the sun. It should then not be too difficult to predict mathematically the large-scale changes in our stellar system. We are already beginning to make some headway with the interpretation of spiral structure in such nebulae as Messier 33, but the lack of information on the cross-wise motions makes it difficult to check the theoretical calculations.

When Stars Meet

How often, on the average, does a star come sufficiently close to our sun to change its course appreciably? We know fairly well the separations and velocities of the stars. We can then compute without much difficulty how often a star will pass within the distance of Neptune from our sun. Such close approaches are rare. Our sun will, on the average, suffer only one in ten thousand cosmic years. The total effect probably would be very slight indeed. The chances are that the passing stars would be fainter than our sun and while the event would be front-page news for a while no permanent harm of any sort would be done. After the visit our sun with its flock of planets would move in a direction that would deviate by only twenty degrees from its original path.

What are the chances that our sun would be hit by a passing neighbor? If that were to happen the results would almost certainly be catastrophic to life on the earth. But we probably have more immediate worries ahead of us, for the average interval between actual collisions of stars the size of our sun is of the order of one billion cosmic years or 200,000,000,000,000,000 solar years!

The rarity of the phenomenon is best illustrated if we note that in our galactic system, with its two hundred billion stars, a collision between any two stars will occur only once in a million years. If we consider that there are some regions of our galaxy where the stars are closer together than in our neighborhood and that some stars have much larger target areas than our sun, we might concede a somewhat higher probability for collisions. It is however very unlikely that collisions take place more frequently than once in ten thousand years in any one galaxy.

From these simple computations it would seem that our chances of being put out of commission through a direct hit, or close approach, are very much less than the continued risk of being destroyed by comparatively small internal changes in the sun. As small a change in the sun's total brightness as one magnitude would automatically result in a change of the average temperature of the earth by seventy-five degrees centigrade. Such a change would not alter the planetary system as a whole, but it is improbable that life at the surface of the earth could adjust itself to an average temperature around the boiling point of water, or to conditions prevailing at fifty degrees centigrade below zero. A mild variability of our sun, something very much less drastic than a nova explosion, could easily put an end to all life on the earth.

But let us get back to our subject—stellar encounters. We have found already that spectacular close approaches are probably rather insignificant. The chances are that our sun will suffer only once in one million cosmic years from an encounter that would swing it by a right angle from its original path. We should, however, not forget that the path of our sun is continually being changed to some extent by more distant passages. A single star passing at a distance

of one light year will change the direction of the sun's motion by somewhat less than one minute of arc. In the course of time the number of encounters within a few light years of our sun is however quite large. Computations show that the total effect of all encounters at minimum distances less than ten to fifteen light years between our sun and other stars will, in the course of one of our cosmic years, be about equal to the total effect produced by a single encounter of our sun and another star at a distance of one hundred or two hundred astronomical units. The greater importance of the unspectacular distant passages is demonstrated by the fact that a single encounter at a distance of one hundred astronomical units should on the average happen only once in twenty million million solar years or one hundred thousand cosmic years. It is quite clear that we might as well forget about the single right angle encounters and head-on collisions, and remember that the distant passages are far more effective.

Do Clusters Break Up?

The motions of the stars in our galaxy show characteristic features that are related to their physical properties. The massive *B* stars appear to move in almost circular orbits around the center of our galaxy; the *A* stars tend to move in groups and the faint dwarfs run at great speeds in almost all directions. You might perhaps think that we have here a statistical relation between the mass of a star and the amount by which its motion deviates from pure circular rotational motion. That picture is, however, rudely disturbed if you consider the cluster type Cepheids or the *M* giants. Here you find stars that weigh at least five times as much as our sun, but race around in a most undignified way with average speeds that differ widely from the circular motion exhibited by the *B* and *A*-type stars.

Our galaxy has not been rotating sufficiently long for the interchange of energy between stars of different types to become effective. From our considerations of stellar encounters it would seem very unlikely that the stars would show so much individuality in their motions if our galaxy had existed in its present form for as many as ten thousand cosmic years or two billion solar years.

Our part of the galaxy is characterised by the presence of many loosely connected galactic clusters. Consider, for example, such clusters as the Hyades or the Pleiades. After our considerations of the disruptive effects of stellar encounters these clusters would hardly seem very stable objects. The Hyades cluster is relatively so close to us that we have not only accurate measurements of the motions of the brighter members, but also a rather complete census of the total membership of this cluster. The densest part of the cluster lies at one hundred and thirty light years from the sun; it contains at most one hundred and fifty members within a distance of fifteen light years from its center. The motions of the individual stars differ by not more than half a kilometer per second from the average total motion.

We can readily predict what should happen to the Hyades Cluster in the course of the next ten or twenty cosmic years. The cluster should stay fairly close to the plane of our galaxy and move therefore in a region where the stars are probably as widely spaced as they are for the vicinity of the sun. We can easily compute how frequently a field star will pass through the cluster or how frequently one of them will pass by at a given distance.

Before we trace the effects of encounters on star clusters we should first look a little closer at the mechanics of a cluster free from intruders and passerbys. A cluster star that wanders slowly away from the rest of the group will generally be pulled back by the attraction of the whole mass.

The cluster tries desperately to preserve its unity. But there is a villian in the piece! We know from observations on galactic rotation that the stars in the vicinity of the sun are all subject to the pull from the galactic nucleus. The parts of the cluster that are closest to the central nucleus of our galaxy will feel more of the nuclear pull than those that are farther away. The general galactic forces will tend to shear the cluster apart. It becomes a regular tug of war. Can the force of attraction produced by the cluster as a whole pull hard enough to counterbalance the disrupting "tidal" forces from the galactic nucleus? If the answer is, yes, the cluster would hold together, but if not, then the cluster should soon be disrupted and its members strewn far and wide.

It takes some mathematical juggling to find where the dividing line between stable and unstable clusters will lie. A certain critical average density is computed. A cluster for which the average star density is less than the critical density cannot possibly stay together, but one with an average density above the critical value will generally have enough pull of its own to withstand the insidious disruptive forces from the galactic nucleus. A cluster for which the average density is equivalent to three solar masses for a cube ten light years on each side should stay together, if, in the course of time, it does not come much closer to the galactic nucleus than does our sun.

What will be the probable effect of encounters between clusters and stars of the general field? The dimensions of the cluster will in general be large and the passing field star will therefore not affect all cluster members in the same way. Two cluster stars that were originally pursuing strictly parallel paths will probably move after the encounter in slightly diverging orbits. The net result of each encounter will be to "loosen up" the cluster. This will tend to weaken

the cluster's attraction on its members and the general galactic tidal force may then get a chance to do its disruptive work.

The Hyades cluster is probably "safe" for at least ten more of our cosmic years or two billion years. By that time the encounters with field stars will have done enough preliminary softening up to bring the cluster to the brink of disruption. Sometime between ten and fifteen cosmic years hence the galactic tidal force will become strongly effective. We should like to predict that five billion years from now you will look in vain for the remnants of the Hyades cluster wherever you may search the galaxy.

The average densities for the Pleiades and Praesepe are more than ten times as high as that of the Hyades. These clusters will be able to withstand the disruptive tidal forces from the galactic nucleus for a much longer time, but their lifetime will not be longer than a hundred cosmic years.

Are there any denser clusters that might take the place of the Hyades and Pleiades clusters? Probably not. The globular clusters should hold together fairly well, but they are very rare.

Might it not be possible that other Hyades or Pleiades might be formed? We do not pretend to know from where the clusters came and how they were born, but from a purely mechanical point of view it seems very unlikely that a workable mechanism could be found for the building up of clusters by chance encounters of unattached stars. Apparently we must conclude that the galactic clusters are a vanishing species that shall have disappeared a hundred cosmic years hence.

We have of course no information about the numbers of galactic clusters that were in the sky at the time when the first cockroaches began to march over the face of the earth, a time which, according to the paleontologists, is about two

and a half cosmic years ago. We know even less about the make-up of our galaxy at the time of the birth of our earth; an event which happened presumably some twenty cosmic years ago. The rate of disruption for the galactic clusters that we know today is so high that it would seem extremely unlikely that our galaxy could have existed in its present form for much longer than fifty of our cosmic years. We would hardly expect such buoyant signs of "youth" if our galaxy had turned around its center for several hundred cosmic years. The very fact that we find a fair percentage of all known stars of spectral class *A* in clusters of various degrees of concentration is the best available proof that our galaxy cannot have existed in its present form for much longer than fifty cosmic years, or ten billion (10^{10}) solar years.

The Expanding Universe and the Cosmic Time Scale

An upper limit to the "age" of our galactic system has just been indicated by the discussion of star clusters. A lower limit comes from the figure for the age of the earth, as found from geological considerations, since the galactic system could hardly be younger than our own earth. Geologists have found from studies of radioactive decay of minerals that the earth was probably formed some three billion years ago. It is rather cheering that the minimum value provided by the earth, three billion years, is not far different from the maximum value, ten billion years, found from the study of star clusters. It would seem that our galaxy has existed so long that the sun must have completed at least ten to twenty circuits around the galactic nucleus, but that it is very unlikely that the sun has had enough time to complete more than fifty circuits.

The cosmic time scale which assigns an age to our galaxy of the order of ten billion years is confirmed independently

from several sources. The most spectacular confirmation comes not from observations in our own galaxy, but from the observed motions of other galaxies. Twenty-five years ago astronomers at Flagstaff and Mount Wilson noticed that the spectra of some of the fainter external galaxies showed a very peculiar behavior. The spectra resembled closely that of the sun, but the surprising thing was that the absorption lines were in most cases shifted toward the red end of the spectrum. The fainter galaxies generally exhibited the greater shifts. Displacements that are so large that the *K*-line of ionized calcium—which is normally at 3933 angstrom units—is found near the normal position of the hydrogen line at 4341 angstrom units have been observed for some of the more distant galaxies.

A detailed discussion of this red shift is out of place in a book on the Milky Way, but it is clear that the motion away from our galaxy of all the external galaxies can be explained as an expansion of the entire system. Working back from the observed relation between the velocity of recession and the present distances of the galaxies we can estimate how long the universe of galaxies may have been expanding. These computations show that, if the red shift is explained as a velocity shift, the expansion of the universe of galaxies would probably have begun some three billion years ago. The close agreement of this value of the cosmic time scale with our previous estimates is indeed encouraging, especially since the new evidence is of an entirely different character from what we had so far presented.

Before we begin to feel too vain about the way in which the pieces of our cosmic jig-saw puzzle are fitting together, we should point to some of the weak points in the argument. What is it that we really observe in the case of the faint galaxies? The basic observation is that the spectrum lines are shifted progressively further toward longer wave-

lengths as we observe more distant systems. Such observations can be explained most naturally by an expansion of the whole universe of galaxies. But it pays to be cautious when distances are measured in terms of tens or hundreds of millions of light years and velocities in tens of thousands of miles per second, and we should not ignore alternative explanations.

The hypothesis of the expanding universe has the dignifying sanction of the general theory of relativity. That approval in itself is not enough, for the frame work of the relativity theory can also support a non-expanding universe.

If we wish to interpret observations of distant galaxies with the aid of known laws of physics, we should ask if these "laws" apply strictly to our case. The observational basis for the quantum theory of radiation lies in experiments made in physical laboratories on the earth. However well equipped these laboratories may seem to us, we must admit that they are ridiculously small in terms of cosmic dimensions. In the physical laboratory a light quantum or an atom is never left alone for any appreciable amount of time. There are always other atoms and other quanta around to disturb it and even the largest test tube looks microscopic on the cosmic scale.

We gain confidence in our laws of atomic physics and radiation when we find that they apply without apparent need of modification in our local galactic system. The first unusual observation is that of the red shift in the spectra of distant galaxies. A true expansion of the universe of galaxies offers the most obvious explanation for this observation, but there are others that cannot be disregarded. A quantum seems to hold its energy completely for a fraction of a second in the laboratory and even for a few thousand years in our own galaxy. But a slight leak, too small to be detectable from observations in the laboratory, might add

up to a considerable amount when we come to intervals of ten million years and more. A leaking quantum would presumably lose energy and according to the precepts of the quantum theory, it should become of longer wave-length —and hence redder—as it progresses through space.

We are not advocating the substitution of the leaking quantum theory for the expanding universe hypothesis. We wish only to emphasize that the red shift by itself cannot be construed as positive proof for the expansion of the universe. The 200-inch reflector on Mount Palomar may yield some vital evidence pro or con, but the observations that are available today are not conclusive.

Stellar Evolution and the Cosmic Time Scale

Our estimates for the cosmic scale have been based on data from stellar motions and the arrangement of stars in systems. What about the stars themselves? They ought to have some voice in the matter, for they are asked to supply energy for millions and millions of years. It is all well and good to talk in terms of ten billion years, but can the stars keep shining for so long a time?

Other books in the series will consider carefully the processes by which our sun and other stars are continually being supplied with energy for radiation. The familiar processes of chemical burning have no place in the scheme. It is so hot in stellar interiors that the atoms are stripped of most of their outer electrons. Transformations as superficial as those of molecular chemistry can only take place in the atmospheres of some cool stars and in our laboratories on the earth, but not in stellar interiors. At the high temperatures prevailing inside the stars, physics looks for the source of stellar energy in the changes that must take place in the atomic nuclei. The interior temperature rises steadily from only six thousand degrees at the surface of the sun to

some twenty million degrees centigrade in the central regions. The atomic nuclei, freed from most of their customary neutralizing entourage of electrons move at such speeds at the tremendously high central temperatures that violent changes occur when two such nuclei collide. Collisions between hydrogen nuclei—the protons—and carbon nuclei set into operation a series of nuclear reactions that appear to provide much of the radiation necessary to keep our sun shining at its present rate.

According to the cycle of energy generation proposed by Bethe of Cornell the collision between a carbon nucleus and a proton will lead to the formation of a nitrogen nucleus, which, because of its subnormal weight, is rather unstable. The nitrogen nucleus will collapse by sending out a positive electron, or positron, and settle down temporarily as a slightly overweight carbon nucleus. Another hydrogen nucleus or proton—there are always plenty of protons inside the stars—comes along and changes the overweight carbon nucleus into a regular nitrogen nucleus. This nucleus will change, as soon as it meets with another of our omnipresent protons, into an unstable oxygen nucleus which sends out another positron, and becomes a quasi-nitrogen nucleus. A fourth and last proton in the series is annexed and the resulting atom is split into two parts. One part is the initial carbon nucleus and the other part is a stable helium nucleus or alpha particle.

For those who understand the symbolism of nuclear physics we write down the chain of reactions as follows:

$$
\begin{aligned}
{}_6C^{12} + {}_1H^1 &= {}_7N^{13} \\
{}_7N^{13} &= {}_6C^{13} + \epsilon^+ \\
{}_6C^{13} + {}_1H^1 &= {}_7N^{14} \\
{}_7N^{14} + {}_1H^1 &= {}_8O^{15} \\
{}_8O^{15} &= {}_7N^{15} + \epsilon^+ \\
{}_7N^{15} + {}_1H^1 &= {}_6C^{12} + {}_2He^4.
\end{aligned}
$$

The lower subscripts refer to the atomic numbers, the upper ones to the atomic weights.

These nuclear reactions, which can be predicted on theoretical as well as observational grounds, are probably the most common reactions in the interior of our sun. We have, however, not yet told the whole story. We started with a carbon nucleus and we ended with a carbon nucleus. The net result of our efforts has been that four hydrogen nuclei or protons have been transformed into a single helium nucleus and two positive electrons. The two positrons will probably not be very long lived, but the helium nucleus is one of the most stable of all atomic building blocks.

The point is that the total weight of the four single protons which have disappeared is nearly one per cent more than that of the helium nucleus and the two positrons together, which have put in an appearance. Where did the mass go that was lost in the shuffle? It was changed into short wave radiation and escaped as a by-product of the several nuclear transformations. According to modern astrophysics the source of energy of our sun, and other stars of the main sequence, can be found in the energy that is released during the building up of helium nuclei out of protons. In this chain of reactions the carbon atom plays the part of an innocent bystander, or, technically, of a catalyst.

The supply of hydrogen in our sun is probably enormous. According to Stromgren nearly forty per cent of the sun's mass consists of hydrogen and, since hydrogen is the lightest of all elements, the hydrogen nuclei or protons far outnumber the nuclei of all other atoms. Bethe's chain of reactions will start if the temperatures are right and if a small amount of carbon is somehow provided. The supply of protons in the sun is so large that it can continue to radiate at its present rate for almost forty billion years.

Theorists predict that it may even brighten up, and for a while become at least as bright intrinsically as Sirius, but even so, our sun can last certainly for as many as ten billion years.

Bethe's carbon cycle accounts for the energy generative processes for the stars of the main sequence, but probably does not apply to the giants and supergiants. Theoretical studies of conditions in the interiors of the rarified giant stars show rather definitely that their central regions are considerably cooler than those of the dwarfs. If we compare our sun—a typical dwarf *G* star—with the brighter component of the double star system Capella—a typical giant *G* star—we find the diameter of Capella *A* to be ten times that of our sun while its mass is only four times that of our sun. The average density in Capella *A* is therefore less than half a per cent of the average of our sun. It is not surprising that the computed central temperature of Capella *A* is only five million degrees against a value of twenty million degrees for our sun.

Capella *A* is by no means the largest giant star that has been found. There are among the red stars some supergiants that are so big that there would be enough space in their interiors for the orbit of Mars around our sun. The central temperatures in these stars are probably hardly more than one million degrees centigrade. The blue supergiants of absolute magnitudes -5.0 to -6.0 weigh on the average only fifty times as much as our sun and yet their total radiation output exceeds that of the sun by a factor ten thousand. Here the sub-atomic energy dynamos are certainly being worked to the breaking point.

As matters stand at present we are still at a loss to explain how these luminous giants produce radiative energy as abundantly as they do. It seems fairly well established that the carbon cycle cannot work at the low central tempera-

tures of some of the supergiants. Astrophysicists are frankly in the market for a neat transmutation cycle to explain the energy generation in these stars. The suggestion has been made that the supergiants are drawing on their initial supply of the lighter elements such as deuterium, lithium, beryllium and boron and then arrive exhausted at the main sequence, where the carbon cycle begins to operate. Nuclear physics is still such a young science that we should not be too dogmatic in trying to account for the tremendous energy output of the supergiants.

What bearing do all these results have on the cosmic time scale? Two things stand out. First, at the temperatures that apparently prevail in stellar interiors, we know of no mechanism that would allow the stars to change more than one per cent of their total mass into radiative energy. Second, the annual energy output of some of the most luminous giants is so high that they could not possibly continue to radiate at their present rate for even so short a time as two billion solar years. From the cosmic point of view the evolutionary process must be quite rapid for some of the brightest giant stars. Several of the best known supergiants cannot possibly continue to radiate as they are doing today for more than five of our cosmic years.

One naturally wonders if the evolutionary processes in the supergiant stars might not occasionally be slowed down. In other words, do we not find some stars with a total mass at least ten times that of our sun and that yet have the same absolute magnitude as our sun? The available data on masses and absolute magnitudes are quite extensive, but nowhere in our catalogues have we found such stars. It is equally significant that we have also not found any stars with masses equal to that of our sun but with absolute magnitudes around zero. The small spread around the observed mass-luminosity relation is highly significant.

The facts and deductions that we have so far presented indicate that the stars of our galactic system are all in their cosmic infancy. Unless we are willing to admit that stars are being born at present on a great scale, we cannot escape the conclusion that our galactic system as such, as well as the component stars, cannot have existed for much longer than the lower limit of our cosmic time scale, three billion solar years.

We thus arrive at the view that the whole stellar system is just about as "old" as our own earth. This may at first come somewhat as a shock, but a little further consideration shows that it may not be such a bad idea. The researches of the past forty years have shown that it is exceedingly difficult to explain how our planetary system may have been formed. It is rather satisfactory to blame it all on conditions as they were three billion years ago, at a time when, according to the hypothesis of the expanding universe, all matter in the physical universe was packed much closer together than it is at present.

But, you may well ask, why should we not admit the possibility that stars are still being formed? According to the position that we have taken so far, all stars originated at that mysterious epoch, roughly three billion years ago, when a complete universe came into being. If we were ready to admit that stars are still being born, our spendthrift supergiants would give us no problem; we could blame all on youthful exuberance. There are, however, several reasons why most astronomers are reluctant to take this view.

First, there are the difficulties with stars like our sun. According to theoretical calculations by Gamow and others, a star with the mass of our sun will, rather paradoxically, grow brighter as it begins to exhaust its supply of hydrogen for use in the carbon cycle. It should of course

fade when the hydrogen supply gives out, but for some time during the next ten billion years our sun should become fully five magnitudes brighter than it is now. (That will by the way probably mean the end of life on the earth.) If this can happen to a star with the sun's mass, why have we so far not observed any stars of solar mass with an absolute magnitude of zero? If the theory is correct we must admit that we do not observe all possible stages of evolution for stars that weigh as much as our sun.

The second objection against the theory of the continued birth of stars comes from the question of double and multiple systems and star clusters. Luminous supergiants and giants are frequently found in the same system that contains one or more stars like our sun. It is very difficult to understand how a fresh supergiant might be born out of miscellaneous gas and dust in a cluster of several hundred stars. And it is even more trying to suggest ways in which a massive luminous supergiant could possibly condense out of interstellar stuff only a few astronomical units away from an old and well-behaved dwarf star. It seems much more likely that all stars in a single cluster or double star system were brewed simultaneously.

Looking Ahead

You may have felt some dissatisfaction with this chapter because we had to make so many assumptions. Yet we believe that we can defend this activity against the assaults of our critics. In the universe as we observe it, we find certain rules and regularities. We naturally ask what are the consequences of these observed conditions and what changes will take place as time progresses. It is then only a step to speculations about the far and distant past, and the cosmic time scale.

The methodical study of the past of our universe has great value as a stimulant for further research. To increase our knowledge of the cosmos we try to know more about the motions and compositions of star clusters, or the explanations of the red shift for distant galaxies. The search for stars that are unusually bright or unusually faint is stimulated by our realization that the discovery of a few such stars may have important bearings on our ideas about the cosmic time scale. It is essential for science that we realize the limitations of each special field of research, but it is also essential that we do not retreat as soon as there is some doubt about the foundations of our reasoning. Cosmological speculations have been a wonderful stimulant, not only for Milky Way research, but also for the whole of modern astronomy.

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